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Are Wastewater Systems Adapting to Climate Change?

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Research Impact Statement: Findings suggest wastewater managers are building resiliency to the past rather than adapting to future climate change except when regulations compel adaptation.

ABSTRACT: Wastewater (WW) systems are vulnerable to extreme precipitation events; storm-induced WW system failures pollute the environment and put public health at risk. Despite these vulnerabilities, we know very little about how WW managers are responding to current climate risks or to future climate change. This study aims to fill this critical gap in the literature. Data from surveys and interviews were used to understand what WW managers are doing to adapt to the current climate, what facilitates those adaptations, and if they are adapting to future climate change. Findings show most WW managers (78%) are making changes to build resiliency to storms they have experienced in the past (e.g., extra fuel on site, extra staff on call, more training, better communication, adding generators, elevating components, adding capacity); most are not adapting to future climate change. Our work suggests organizational leadership, concern about future climate-related impacts, and experiencing storm impacts drive resiliency changes while regulatory requirements drive adaptation to future climate change. Beyond advancing science, our work offers practical suggestions for building WW system resilience and for increasing WW system's consideration of future climate impacts in their resiliency building efforts.

(KEYWORDS: climate variability/change; sustainability; regulation or policy; resilience; climate adaptation.)

INTRODUCTION

Wastewater systems — including wastewater collection, pump stations, and wastewater treatment plants (WWTP) — play a critical function in society; yet, they are increasingly at risk of failing to protect public health and the environment because they are old, incredibly underfunded (EPA 2008; NACWA and AMWA 2009), and vulnerable to the impacts of extreme events and sea level rise (Patz et al. 2008; Campos and Darch 2015a; Howard et al. 2016). For example, hurricanes caused widespread power outages, flooding, and bypassing of billions of gallons of untreated or partially treated sewage into local waterways (Altimari 2011; Kenward et al. 2013; Wade et al. 2014). But, it is not just hurricanes. High winds and heavy rains are also enough to cause problems. For example, in 2007, summer floods in the United Kingdom overwhelmed wastewater systems putting hundreds of systems out of service (Campos and Darch 2015a) and in 2017, in Seattle, Washington a night of heavy rain sent 180 million gallons of wastewater into Puget Sound (Long 2018). Across the country that same year in Waterbury, Connecticut heavy rain washed five million gallons of raw sewage into the Naugatuck River (Blanks 2017). These failures suggest wastewater systems struggle to manage today's extreme storms; climate change is likely to make things worse with more frequent extreme precipitation events expected in the future (Bates et al. 2008).

To lessen the impacts of current extreme events and to withstand future climate changes requires wastewater managers to institute adaptation actions that

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lessen vulnerability and build resilience. For the purposes of this paper, we define resilience as the capacity to anticipate and prepare for, cope with, recover, and learn from a disturbance (Francis and Bekera 2014), and we define adaptation actions as specific and tangible actions intended to reduce vulnerability, increase resilience, and adapt to the impacts of climate change (Berrang-Ford et al. 2011; Lesnikowski et al. 2011). While scholars have advanced our understanding of how climate change will affect wastewater systems (Butler et al. 2007; Plósz et al. 2009; Langeveld et al. 2013; Campos and Darch 2015a; Weirich et al. 2015; Zouboulis and Tolkou 2015; Howard et al. 2016), how to design wastewater systems to withstand a changing climate (Smith 2009; Mailhot and Duchesne 2010), how to assess and enhance wastewater system resilience under a changing climate (Scott et al. 2012; Schoen et al. 2015; Faust and Kaminsky 2017; Juan-García et al. 2017; Sweetapple et al. 2017), and how wastewater systems might adapt to climate impacts (Gersonius et al. 2013; Campos and Darch 2015a, b; Zouboulis and Tolkou 2015), very little research that we know of aims at understanding what wastewater managers themselves are doing to reduce vulnerabilities, build resilience, and adapt to climate change. This lack of understanding of what wastewater managers are doing, what motivates those actions, and what supports (or impedes) those actions means we do not yet know how wastewater managers themselves are approaching this challenge or what possible entry points may exist to help wastewater managers implement more or different strategies to reduce vulnerabilities, build resilience, and adapt to climate change in practice.

This study aims to begin to fill this gap in the literature. We use an empirical mixed method approach including interviews and a survey of wastewater managers in Connecticut to understand: (1) How are wastewater managers responding to current extreme events? (2) What drives those changes? and (3) Are wastewater managers adapting to future climate change? The following sections include a brief review of the literature, description of Connecticut wastewater systems and the context of the study, the methods used to collect and analyze data, and present and discuss the results. We conclude with recommendations for how to facilitate adaptation to future climate change in wastewater systems.

LITERATURE REVIEW

Well-functioning wastewater systems provide a critical service to society by collecting and treating liquid organic wastes and discharging effluent water of sufficient quality to protect the environment and public health. The combined effects of aging infrastructure and extreme precipitation events contribute to wastewater system failures (Howard et al. 2016); wastewater system failures damage the environment and raise rates of gastrointestinal disease putting public health at risk (Wade et al. 2014; Jagai et al. 2017). Climate change is expected to aggravate these failures by increasing sewer overflows, changing treatment effectiveness, decreasing the absorptive capacity of receiving waters, and exposing more infrastructure to damage and inundation from sea level rise (Butler et al. 2007; Plósz et al. 2009; Nilsen et al. 2011; Arkell et al. 2012; Langeveld et al. 2013; Campos and Darch 2015a; Weirich et al. 2015; Zouboulis and Tolkou 2015; Sweetapple et al. 2017). Despite the prevalence of wastewater system failures and the prospect of more in the future, we know very little about the human dimensions of wastewater systems, especially what wastewater managers themselves are doing to combat today's challenges as well as adapt to future climate change.

While we lack understanding of the human dimensions of wastewater systems, an emerging body of literature explores how to physically engineer wastewater system resilience to the current climate and to adapt wastewater systems to the future. Resilience generally has to do with the capacity to anticipate and prepare for, cope with, recover from, and learn from a disturbance (Francis and Bekera 2014), while adaptation is defined as "the process of adjustment to actual or expected climate and its effects" (IPCC 2014, p. 118). In their review of this literature, Juan-García et al. (2017) found the most common suggested resilience improvements for wastewater systems are added capacity (buffering), equipment backup, maintenance and repair, and asset protection. Suggested adaptations include improved monitoring, planning, and maintenance of the wastewater system and conducting vulnerability analyses (Campos and Darch 2015a, b; Zouboulis and Tolkou 2015), installing more sustainable drainage systems, constructing floodwalls, and "dry-" or "wet-proofing" (Campos and Darch 2015a, b). Both resilience and adaptation suggestions are mostly derived from modeling of wastewater systems under different stresses (e.g., flooding, greater inflows, higher temperatures, etc.) and from reviews of the literature rather than empirical investigation of wastewater manager practices.

A great deal of research has quantified barriers to adaptation in different domains (for comprehensive review of this literature, see Biesbroek et al. 2013). Where adaptation has happened, researchers have quantified adaptation efforts globally (e.g., Adger et al. 2005; Berrang-Ford et al. 2011; Ford et al. 2011) and in individual countries (e.g., Tompkins et al. 2010; Bierbaum et al. 2013), in cities (Bowler et al. 2010; Measham et al. 2011; Dilling et al. 2017), in business and industry (e.g., Linnenluecke et al. 2013), in the transportation sector (e.g., Eisenack et al. 2012), and in the energy sector (Braun and Fournier 2016). The only published literature we found related to this subject for the wastewater sector is Rudberg et al. (2012). Rudberg et al. (2012) was limited in scope relying on interviews with only four wastewater systems in Stockholm, Sweden to explore how the adaptive capacity of wastewater systems influenced whether and how wastewater systems implement adaptive decisions in response to expected climate change. Rudberg et al. (2012) found the inability to justify the expense for the adaptation and the lack of rules requiring adaptation limit adaptation action while knowledge on climate change impacts supports adaptation. While Rudberg et al. (2012) provided a useful reference point, its limited geographic scope and small sample size make generalizations difficult. As such, there remains an urgent need for systematic, empirical investigation of wastewater systems to better understand what the wastewater sector is doing to build resilience and to adapt to climate change. This study aims to begin to fill this critical gap in the literature with a systematic investigation of the actions wastewater managers take to build resilience and adapt to climate change. In this study, we use the term adaptations (or adaptive changes) to mean specific and tangible actions intended to reduce vulnerability, increase resilience, and adapt to the impacts of climate change (adapted from Berrang-Ford et al. 2011; Lesnikowski et al. 2011). These actions may be temporary or permanent structural changes to wastewater infrastructure (e.g., to the collection system, pump stations, or the treatment plant) or they may be changes in practices and procedures resulting from organizational learning (Berkhout 2012).

CONNECTICUT WASTEWATER SYSTEMS

Connecticut has approximately 131 wastewater systems that provide wastewater services for over 2.38 million residents. Connecticut wastewater systems range in treatment capacity from about 5,000 gallons per day to 60 million gallons per day (MGD) with a median capacity of 1.2 MGD. Wastewater systems are regulated by the Connecticut Department of Energy and Environmental Protection (CTDEEP) which also administers the Clean Water Fund (CWF) (i.e., funding from the Clean Water Act) which provides loans to municipally owned systems. In 1998, the state legislature passed An Act Concerning Global Warming Solutions (Public Act 08-98) which led to the 2011 Connecticut Climate Preparedness Plan which recommended that CTDEEP require wastewater systems that receive funding from the CWF to "consider climate change as part of facility planning" (GSC 2011). In 2013, the state legislature made considering sea level rise a requirement of CWF recipients (Public Act 13-15).

Connecticut wastewater systems were chosen, following Flyvbjerg (2006) and Yin (2013), as a paradigmatic case study of wastewater system resilience and adaptation given the recent experience with extreme storms including Sandy and Irene and the state's support for adaptation. Given the support for climate adaptation, we would expect to encounter some adaptation activity among wastewater systems enabling a fuller exploration of the conditions that promote adaptation compared to states where adaptation is less supported.

METHODS

Data Collection

We sought and obtained Institutional Review Board approval for our research (protocol X16-091) that involved both a quantitative survey and qualitative interviews with wastewater system managers (hereafter wastewater managers) to understand wastewater managers' experience with past storms, what actions managers take to prepare, respond, or recover from storms, what facilitates those actions, and if they are adapting to future climate change. The survey questions were developed to assess experience with past storms, risk perceptions regarding future storms and climate change, the characteristics of the wastewater system (e.g., size, location) including the organization (e.g., leadership, culture, available science, etc.), and the broader context (e.g., public or political support, regulatory environment) drawing on relevant theoretical literature on factors thought to drive adaptation actions including risk perceptions and organizational learning (Berrang-Ford et al. 2011; Lesnikowski et al. 2011; Berkhout 2012). To improve measurement reliability and validity, the survey was pilot tested with nine individuals including wastewater managers not in the final survey sample, wastewater experts at the CTDEEP, and experts in questionnaire design in October 2015 (Schultz and Whitney 2005; Perneger et al. 2015).

The survey was revised using pilot testing feedback and the revised survey was administered via email to wastewater managers at 131 wastewater systems in Connecticut from November 2015 to April 2016 (Qualtrics, Provo, Utah, USA) with three email reminders to encourage a response (Dillman et al. 2014). The complete final survey is included as Supporting Information. In total, we received 86 completed surveys from the 131 surveys administered for a 65.6% response rate.

In addition to the survey, from October 2016 to March 2017, we interviewed 29 wastewater managers selected from among a stratified sample of survey respondents (i.e., stratified by inland vs. coastal location, impacted vs. not impacted by past storms, and made changes vs. did not make changes). The interview protocol was tested with four wastewater managers in July and August 2016 after which refinements were made to the protocol before initiating interviews with the final sample (Kirk and Miller 1986). Interviews were conducted by phone and each interview lasted between 35 and 55 min. Interviewees were asked questions about the nature and severity of past storm impacts, the types of adaptive changes made, if any, and motivations for those changes, what helped or hindered making changes, and about adaptation to future climate change. Question development for the latter three themes drew principally on factors thought to drive adaptation actions including risk perceptions, resources, and learning (Berrang-Ford et al. 2011; Lesnikowski et al. 2011; Berkhout 2012). See Supporting Information for survey and interview protocol.

Variable Construction and Analysis of Survey Data

One dependent and multiple independent variables were created from survey questions. The binary dependent variable *Changes* (where 0 = no change and 1 = made change) was constructed from responses to the question, "have you made changes to improve the resilience of your wastewater system." Independent variables were constructed to examine the influence of a range of factors on the dependent variable *Changes.* For example, several impact-related independent binary variables were created including: *Experienced impacts* (where 0 = not impacted and 1 = experienced impacts from past storms), *Lost power* (where 0 = did not lose power and 1 = lost power), *Experienced flooding* (where 0 = did not experience flooding and 1 = experienced flooding), *Bypassed* (where 0 = did not bypass and 1 = bypassed secondary treatment), *Lost access* (where 0 = did not lose access and 1 = lost access to one or more components of the wastewater system), and *Multipleimpacts* constructed as a sum of individual impacts experienced by the system. Other independent variables captured risk exposure *Coastal* (where 0 = not coastal, 1 = coastal) and risk perception (where 0 = not at all concerned, 1 = a little concerned, 2 = somewhat concerned, and 3 = greatly concerned) including for river and coastal flooding, storm surge, sea level rise, and climate change. A combined *Average concern* variable was also created from averaging the level of concern about future impacts across all five hazards. Other independent variables were created to capture organizational factors (*Available budget, Empowered, Organizational leadership, Aging infrastructure, Municipal partners, Up-to-date technology)*, sociopolitical factors (*Local/Regional Policies, State/Federal Policies, Local public support, Local political support*), and knowledge-related factors (*Incentives to learn*, *Climate science, Trusted information source*). These variables were created from Likert scale responses (where 0 = greatly hindered, 1 = somewhat hindered, 2 = neither helped nor hindered, 3 = somewhat helped, 4 = greatly helped) making changes. Finally, a system characteristic, *Average capacity* in MGD, was constructed to control for system size.

Survey data were analyzed using SPSS (SPSS Statistical software Version 22; SPSS, Armonk, New York, USA) using a 0.05 level of significance. Data analysis included descriptive statistics to summarize and explore the data, chi-square tests, independent samples t-test, and nonparametric Mann–Whitney tests to test for independence, differences in means, and differences in medians, respectively, between the dependent variable *Changes* and each independent variable (Noether 1991). Finally, to determine the most important predictors of change at wastewater systems, a logistic regression was performed (Agresti 2013).

Analysis of Interview Data

Interviews were recorded and transcribed (Galletta 2013) and then each coauthor independently reviewed and coded the transcripts using qualitative data analysis software NVIVO 11 (QSR International, Burlington, Massachusetts, USA) (Saldaña 2016). To answer the first two research questions, data were coded to identify (1) what changes wastewater managers implemented, (2) what motivated those changes, and (3) what helped or hindered making changes. To answer the third research question, data were coded for what wastewater managers think about (4) storms, (5) whether or not storms were changing, (6) climate change, and (7) climate change adaptation. Authors adjudicated differences in coding through multiple coding iterations to improve intercoder reliability (Brinkmann and Kvale 2015; Saldaña 2016). For these analyses, we compared systems that made changes to systems that did not make changes. Because anonymity was guaranteed, survey data are reported only in aggregated form and interviewees are referred to by code only.

ADAPTATION ACTIONS AT WASTEWATER SYSTEMS

According to our survey data, most (78%) wastewater managers made adaptive changes; interview data provide insight into the kinds of changes managers made. Nearly 30% (28.6%) of interviewees described several low-cost, temporary, adaptive changes to help prepare for and cope with storm events. These changes include fabricating and installing temporary flood gates and flood proofing doors in advance of storms, *... our local machine shop made up stop gates. ... we just drop them in and it holds back the water* (S24) and *... we went out and we took that foam that comes out in the can and we sealed the hatches as best we could* (S15). Another described purchasing and installing plugs for pump station vents to keep pump stations from flooding: *... we started seeing water entering from vent holes, so we did get plugs, and have them to this day, so we can plug those vent holes off* (S09). Others described topping off fuel tanks, *We'll fill up all the fuel tanks and make sure all the vehicles are fueled up* (S14) or stockpiling fuel in case of an extended power outage:

> A couple of our operators had some empty 55 gallon drums so when the fuel oil was able to be delivered, they filled two 55 gallon drums and left them at two of the stations in the building, which is good because we had to pump out of those barrels into the generator to keep them running. (O20)

Preparation and coping strategies concern not only temporary equipment or temporary modifications to equipment or structures but also temporary operational or staffing changes to help weather storm events. For example, a few interviewees described short-term changes they made to how they operate their WWTP that enables them to maintain permit limits despite receiving higher inflows to the plant during storm events (S32). Still others described how they prepare for storm events by keeping extra staff on call (S16) or on site, *... if there's going to [be] a hurricane ... or nor'easter. What we do is typically we'll leave guys here at the facility rather than risking not being able to get to work* (S14) in advance of a storm.

In addition to temporary changes, 62% of interviewees reported making permanent changes in how the system is run or permanent changes to physical components designed to improve resilience to extreme events. For example, some systems are conducting more or ongoing trainings (O20 and S16) to better prepare for and respond to storms when they occur. Others are saving more money to fund emergency repairs (DE18) as a strategy to improve resilience to extreme events. Still others made small-scale, permanent changes to reduce rates of infiltration such as sealing manholes that help them to cope with extreme events, [T]*here were some manholes that weren't sealed. ... we've addressed those, and that really helped us get through the major rains we've seen since then* (S06). Others described costlier changes including buying new pumps to have on hand for emergencies (DE18), buying new generators to provide backup power (S23), and buying new pumps that can withstand flooding, as described by this interviewee:

> [We changed to] the existing raw sewage pumps that we have right now because [they] are submersible pumps and if they do get submerged underwater, they're designed to operate the same. The ones we had prior to these were not submersible. (E17)

Other interviewees described elevating system components like generators, electrical systems, and control panels that experienced flooding in the past to make that equipment more flood resistant in the future:

> [W]ith the flooding ..., we did lose a few generators, and when we replaced them, ... one we put up on a cement pier using the high water mark from that [flood] event to at least if it happened again, our electrical service, and our generator wouldn't have that effect. (S09)

Finally, several interviewees described major changes undertaken at their facilities. These changes typically involved redesign and subsequent rebuilding of the entire WWTP costing the system many millions of dollars (S12, S13, S21, S22).

DRIVERS OF CHANGE AT WASTEWATER SYSTEMS

Statistical analysis of the survey data, summarized in Table 1, helped us understand what influences adaptive change at wastewater systems. Results show that managers who made changes had greater average concern about future climate-related risks (mean concern 2.48 vs. mean concern 1.36) and about climate change specifically (median 2, "somewhat or greatly concerned" vs. 0, "not at all concerned") than managers who did not make changes. Results also show that having local public support, strong organizational leadership, up-to-date technology, and aging

TABLE 1. Independent samples *t*-test, Mann–Whitney, and chi-square test results of wastewater managers that made changes.

Variables		Did not make changes (n = 19)	Made changes (n = 67)	Test statistic	*p*-Value
Average capacity (million gallons per day)	Mean (SD)	4.47 (5.31)	6.36 (7.65)	−1.005[1]	0.325
Average concern	Mean (SD)	1.36 (0.486)	2.48 (0.799)	−7.519[1]	<0.001
Concern for climate change	Median (SD)	0.0 (0.562)	2.0 (0.893)	193.00[2]	<0.001
Local public support	Median (SD)	2.0 (0.501)	3.0 (0.612)	67.000[2]	<0.001
Local political support	Median (SD)	2.0 (0.478)	4.0 (0.860)	87.000[2]	<0.001
Empowered	Median (SD)	2.0 (0.459)	3.0 (0.783)	81.000[2]	<0.001
Organizational leadership	Median (SD)	2.0 (0.577)	3.0 (0.704)	104.500[2]	<0.001
Up-to-date technology	Median (SD)	2.0 (0.452)	3.0 (0.687)	58.500[2]	<0.001
Aging infrastructure	Median (SD)	2.0 (0.772)	3.0 (0.839)	95.500[2]	<0.001
Experienced impacts	Median (SD)	2.0 (0.621)	4.0 (0.517)	69.500[2]	<0.01
Experienced flooding				16.877[3]	<0.001
Coastal				5.744[3]	0.017

[1]Independent samples *t*-test.
[2]Mann–Whitney test.
[3]Chi-square test.

infrastructure, and being empowered to make changes to the wastewater system were more helpful for managers who made changes compared to those that did not make changes (median = 3, "somewhat helped" vs. 2, "no effect"). Having local political support and experiencing impacts from past storms was more helpful for managers who made changes vs. those that did not make changes (median = 4, "greatly helped" vs. 2, "no effect"). Finally, survey results indicate experiencing flooding and being located along the coast were significantly associated with managers who made changes; treatment capacity was not significantly associated with making changes (i.e., larger systems were not significantly more likely to make changes compared to smaller systems).

While numerous factors were significant when tested individually, when controlling for other variables in a logistic regression, the most important predictors of change at wastewater systems were *experiencing impacts* from past storms, having strong *organizational leadership*, and expressing greater *average concern* about future climate-related risks (see Table 2). These three predictors explained 89% of the variance in the dependent variable made *changes* (for additional regression results, see Supporting Information).

Interview data help shed light on how impacts from past storms, leadership, and concern about future risks influence decisions to make changes to the wastewater system. First, among interviewees who made changes, most (78.6%) experienced disruptive, damaging impacts from past storms including significant flooding at the plant or at one or more collection system pump stations, high inflows at the plant that necessitated bypassing, and lengthy power outages. Often these systems experienced either multiple impacts from the same event (e.g., power loss and flooding, flooding of one or more pump stations and loss of access) or multiple impacts from separate events (e.g., experienced flooding and bypassing from one storm then experienced an extended power outage during a different storm). This connection between multiple impacts and change is echoed in the survey where managers who made changes experienced a median of three impacts compared to a median of one impact for those that did not make changes (Mann–Whitney $U = 297.5$, $p < 0.001$). Disruptive, damaging impacts from past storms helped to motivate change as indicated by these interviewees:

> It's been reactionary. We had a storm event at [that impacted] that station. After that first

TABLE 2. Final regression model with log odds, standard errors, and confidence intervals.

	Final model made changes				
	Coeff.	SE	*p*-Value	Exp(*B*)	95% CI for Exp(*B*)
Experienced impacts	2.194	0.925	0.018	8.973	(1.465, 54.973)
Average concern	4.667	2.272	0.040	106.394	(1.238, 9,141.495)
Organizational leadership	2.767	1.338	0.039	15.904	(1.156, 218.879)
Constant	−20.897				

> flooding event, then we put in procedures to address that particular flooding. (O20)
>
> We do our after action reports on each event, which is part of the closing up of the Emergency Operations Center. And we incorporate that into our training, or [into our] standard operating procedures ... anything that happens once to us ... we identify it and add it to our bag of tricks. (S23)
>
> It [Hurricane Bob] did change a few things ... when the plant was upgraded in the 1990s they raised everything above 100 year flood plain ... and installed a new berm to keep plant from flooding. (S16)

Second, organizational leadership evident in two-thirds (66.7%) of systems that made changes enable wastewater managers to do what is needed to keep the system functioning well as conditions and demands on the system change. Organizational leadership manifests in these systems in two ways: wastewater managers are entrusted and empowered as leaders to make good decisions by those who oversaw the wastewater system (e.g., Water Pollution Control Authority [WPCA] or Town Council) and wastewater managers create a culture of continuous change within the wastewater management organization. Examples of wastewater managers entrusted and empowered to make good decisions include:

> They're [the WPCA are] there in the background ... we do run everything by them, but they trust staff and the people they have working for them to make the best decisions for what's best for the facility. (S19)
>
> We've got an eight member commission here ... we meet monthly. We go over what we're trying to accomplish and where we're going. But they really do leave that [the technical aspects] up to us. (S32)

In addition to being empowered to make decisions, mangers who made changes often create a culture of change that is geared toward continuous improvement. In this way, managers create an operating space open to new ideas and to experimentation (Wilby and Vaughan 2011) as illustrated by these interviewees:

> I always tell people here if they want to try something, go ahead ... If it works, great. If not, we ditch it. 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. (O20)
>
> I've got my staff heavily involved ... because you get everyone's opinions and ideas and as a group collectively you come up with a lot more ideas or problems that you didn't know existed out there that you can try to correct. (S19)

Being empowered to make decisions and having a culture of continuous improvement means these wastewater managers tend to be proactive in making changes to keep the system functioning well as conditions and demands on the system change.

Finally, interview data were more mixed in terms of concern about future climate-related risks as a driver of change. On the one hand, future climate-related risks (e.g., climate change) was a concern for some (28.6%) interviewees — *we've got concerns about global warming* (O20) and *Climate change* [concerns me] *a little bit because if you get more severe storms, electrical interruptions* [may be more frequent]. *That's a bigger deal* (S16). This concern did drive some interviewees to make changes. For example, one interviewee said, ... *that* [storms getting more severe] *is one of the reasons we're doing the upgrade* [at the] *main pump station and the plant here. So we're hoping that'll help us* (S32). On the other hand, some interviewees explicitly said that future climate-related risk was not a motivator for making changes. For example, one interviewee said, *I mean global warming, all this stuff, good, it's all important in the big scheme of things but* [it is] *not relative to my plant* (W05) while another said, *I don't see it at this point in time ... if there were a pump station that were continuously flooded, yeah, I think you'd have to do something .... But it really has nothing to do with climate change* (DE18).

While concern about future climate-related risks was not a huge driver of change, interview data showed that more than half (57.1%) of the interviewees who made changes think there has been a change in the intensity of storms, whereas the majority (71.4%) of interviewees who did not make changes think storms are about the same as they have always been. To illustrate this point, interviewees who made changes and think storms are different now said the following:

> It appears that the 50-year storms now seem to be the 25-year storms. And 100-year storms seem to be the 50-year storms type of thing. So we seem to be seeing more severity. (S06)
>
> It just seems that storms that we're getting seem to be more intense. Maybe not as many of them but they seem to be more intense. (S12)
>
> I think they [storms] are getting more severe and more regular. (W05)
>
> I would have to say that the weather might be a little bit more extreme for this last thunderstorms ... in the past 10 years, we've had 500 year events, with regularity. (S23)
>
> ... they talk about the 100 year storm. Well, we're having 100 years storms every couple of years. (DE18)

Unlike interviewees who made changes, interviewees who did not make changes often expressed the belief that storms are about the same as they have always been as indicated by these interviewees: *I think they're probably about the same as they've always been* (E17) and *I think they are about the same in our area* (S27).

ARE WASTEWATER MANAGERS ADAPTING TO CLIMATE CHANGE?

Interview data reveal half (50%) of wastewater managers who made changes did so to improve resiliency to withstand the worst storm impacts experienced by the wastewater system to date. One interviewee put their resiliency efforts this way: *Our focus has been … hardening facilities* to increase … *survivability due to extreme weather events. I think we basically call it, the new buzz term is, resiliency* (S23). To improve resiliency and increase survivability often means thinking back to prior experiences and making the system more resilient to those events. For example, one interviewee described that they put a generator that had been flooded out in a prior storm *up on a cement pier using the high water mark from that event* (S09). Similarly, another interviewee said that when they replaced a generator that was flooded during Hurricane Sandy they … *put the new one … on three foot metal staging so it brought it up above that* [Hurricane Sandy flood] *line. They also raised control panels … above the storm Sandy level* (S15). Other systems are sealing manholes or replacing sewer lines to reduce I&I (S06), adding generators (S21, S23), and stockpiling additional funds to pay for emergency repairs (DE18). Rather than proactive adaptive actions, these actions are reactive, incremental, and are aimed at sustaining capacity to provide reliable wastewater treatment and to meet permitting requirements (Berkhout 2012). While these changes likely will increase survivability to storms similar to those they have experienced in the past, the changes may not be sufficient to withstand future climate change.

When asked about making changes specifically to adapt to climate change, many wastewater managers responded in either of two ways. Some wastewater managers responded by saying that they are not doing anything specifically to adapt to climate change because they did not "see" climate change impacts as relevant to their system. For example, one interviewee said, *I associate climate change with increasing of the water* [sea level rise]*, and I'd say that it sounds more coastal to me* (S09) while another said, *I mean global warming. All this stuff. It's all important in the big scheme of things but* [it is] *not relative to my plant* (W05), and a third interviewee said, *right now I guess I don't look at it that long-term. I don't really see it* [climate change] *affecting it much unless it's at my door* (S15). For other wastewater managers, climate change could be relevant but they want to see some measurable climate change impact before they consider doing something in response to climate change. For example, one interviewee said, *there's no long term trend data that allows you to say,* [the increase in] *river levels* [is] *because of increasing ocean levels* … (S21), while another said, *if there were a pump station that were continuously flooded, yeah, I think you'd have to do something* (DE18). While these wastewater managers are aware of climate change, they see it as a distant threat in time or space (Brügger et al. 2015). For these wastewater managers, there is no directly attributable climate signal relevant to their wastewater system that requires a specific adaptation — a necessary precursor to climate change adaptation for organizations (Berkhout 2012; Biesbroek et al. 2013).

About a third of interviewees who made changes are adapting to a changing climate; most (80%) are doing so because new state regulations require adaptation actions. These new regulations require that wastewater systems that receive CWF funds make wastewater infrastructure resilient to … the effects from severe weather events and expected climate change impacts including, but not limited to, increases in the frequency and severity of precipitation events, flooding, storm surge, wave action, and sea level rise (CTDEEP 2017, p. 1). Specifically, all state-funded wastewater projects must adhere to minimum flood protection levels in *TR-16 Guides for the Design of Wastewater Treatment Works* (TR-16) (NEWIPCC 2016; CTDEEP 2017). TR-16 requires that critical wastewater equipment and structures are flood protected to the 100-year storm plus three feet or to the 500-year flood elevation (NEWIPCC 2016). Interviewees with state-funded projects mention the design guide (TR-16) or state regulations as the driving force for decisions to elevate infrastructure to required levels:

> Our upgrade that is in the planning stages and includes one hundred plus three is driven by state requirements. (S16)

> the state … [is] requiring [us] to put in resilience flood measures. The plant itself has a berm around it. So currently it's protected for the 100-year [storm] … Chemicals have to be five feet above the 100-year [storm]. Critical facilities like the headworks, primaries so that you can maintain primary treatment and not have the flood waters overwhelm the facility … . So that's kind of the driving force behind it. (S12)

> The facility is currently under design for a $15 million [upgrade] … and I know that there's new

regulations for the [flood levels]. I think it's 100-year plus three. (S10)

Without state rules requiring projects that receive CWF funds be designed to withstand expected climate change impacts including sea level rise, it is unlikely these wastewater systems would be adapting to climate change. This relationship between regulation and adaptation action is consistent with the adaptation literature (Wilby et al. 2009; Wilby and Vaughan 2011). When rules require incorporation of climate change, utilities comply.

DISCUSSION AND CONCLUSION

We used a mixed method approach combining a quantitative survey and qualitative interviews with wastewater managers to understand what wastewater managers are doing to adapt, what facilitates those adaptive actions, and if they are adapting to future climate change. Our findings suggest that two-thirds of wastewater systems are adapting by implementing temporary and permanent structural changes within the collection system and treatment plants as well as changing practices and procedures to better prepare for, cope with, and recover from storms. Similar to other research that finds that the severity of prior negative experience with flooding matters as a driver of flood response (Berkhout 2012; Bubeck et al. 2012), the vast majority (~80%) of systems that made changes experienced disruptive, damaging impacts from storms. Besides past storm impacts, organizational leadership and a culture of learning helped wastewater managers implement changes consistent with characteristics of adapting organizations (Wilby and Vaughan 2011; Berkhout 2012). Finally, while nearly a third of wastewater managers expressed concern about future climate-related risks, fewer (20%) said future climate change specifically motivated the changes they made. Wastewater managers that made changes mostly did so to improve system resiliency to past extreme events.

Wastewater managers are concerned about building resiliency, but these actions are mostly reactive. Nearly two-thirds of wastewater managers who made changes are looking to past impacts to guide changes rather than thinking about what climate change may have in store for the future (Milly et al. 2008; Hallegatte 2009). So, while "building resilience" has taken hold in the wastewater sector as the new "buzzword" and a strong motivator for making changes, adapting to past storms may not protect wastewater systems from future climate risks. This suggests that language matters. "Building resilience" may be insufficient if what is really needed is "adaptation to climate change" or "climate resilience" (Hill and Kakenmaster 2018, p. 61).

Our results suggest that wastewater managers are aware of climate change but that managers generally see climate change as a distant threat in time or space (Brügger et al. 2015). For these wastewater managers, there is no directly attributable climate signal relevant to their wastewater system that requires a specific adaptation. Not perceiving a climate signal constrains climate change adaptations as perceiving a signal is thought to be a necessary precursor to climate change adaptation for organizations (Berkhout 2012; Biesbroek et al. 2013). While wastewater managers do not yet see a climate signal, this finding differs from Arnell and Delaney's (2006) study of UK water companies and Rudberg et al.'s (2012) study of Swedish wastewater organizations. In both of those studies, water managers in the UK and wastewater managers in Sweden recognized a climate change signal affecting the water supply and demand balance or the wastewater system.

Wastewater managers that are adapting to climate change are primarily driven by regulatory requirements tied to financing of wastewater system improvements. The positive influence of regulatory or policy drivers motivating adaptation to climate change has been stated elsewhere (Rudberg et al. 2012; Jordaan 2018); nevertheless, given policy and regulatory changes have influenced and made possible (with funding) adaptation in the wastewater sector, this is an important avenue to pursue to increase adaptation. With this recommendation, an important challenge is expanding the cadre of systems that pursue CWF funding (which triggers adherence to the new guidelines). Few systems benefit from these funds given the heavy administrative load and the requirement that municipalities must cover a portion of the costs. Alleviating these constraints may open up CWF funding to more systems and broaden support for climate adaptation. Beyond funding, wastewater systems may benefit from more exposure to information and training about potential climate changes and their impacts on wastewater systems. Such training may help overcome knowledge gaps about climate change that could be inhibiting adaptation (Rudberg et al. 2012) and help expose wastewater managers to resources and regulations for adaptation.

While this study has advanced what we know about wastewater systems and adaptation actions, more work is needed to more fully understand what drives or impedes climate change adaptation in the wastewater sector and to explore in more depth wastewater managers' understanding of and perceptions about resilience and climate change. In addition, more work is needed to investigate wastewater systems in other states and countries to understand how comparable these results are to other regions. Finally, more work is needed to explicitly compare resiliency and adaptation actions between infrastructure sectors to broaden our ability to derive theoretical and practical insights about what drives climate adaptation among water, wastewater, and other infrastructure systems.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Survey instrument, interview protocol, and additional regression results.

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