Climate Change and Onsite Wastewater Treatment Systems in the Coastal Carolinas: Perspectives from Wastewater Managers

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ABSTRACT: Nearly one-half of the residents of North and South Carolina use decentralized or onsite wastewater treatment systems (OWTS). As the climate changes, coastal communities relying on OWTS are particularly vulnerable, as soil-based wastewater treatment may be reduced by water inundation from storm surge, sea level rise and associated groundwater rise, and heavy rainfall. Despite the vulnerabilities of OWTS to increased precipitation and sea level rise, there is little known about how onsite wastewater managers are responding to current and future climate risks. We conducted interviews with wastewater operators and installers and health regulators to understand the functioning, management, and regulation of OWTS in the current climate, challenges with rising sea levels and increases in extreme weather events, and what adaptation strategies could be implemented to mitigate negative impacts. Our results indicate that heavy precipitation and storm surges cause malfunctions for conventional septic systems where traditional site variables (e.g., soil type or groundwater level) are undesirable. Weather and climate are not required regulatory factors to consider in system selection and site approval, but many OWTS managers are aware of their impacts on the functioning of systems, and some are preemptively taking action to mitigate those impacts. Our findings suggest that filling gaps in the current communication structure between regulators and homeowners relying on OWTS is critical for coastal communities in the Carolinas to build climate resilience into decentralized wastewater infrastructure.

SIGNIFICANCE STATEMENT: This research aims to understand the functioning, management, and regulation of onsite wastewater treatment systems in the current climate, the challenges to these systems caused by rising sea levels and increases in extreme weather events, and the adaptation strategies that can be implemented to mitigate negative climate impacts. These results can be used by state government agencies, municipalities, and private sector wastewater managers to improve the resiliency of onsite wastewater treatment systems.

KEYWORDS: Social science; Climate change; Adaptation; Water resources

1. Introduction

Onsite wastewater treatment systems (OWTS) play an essential role in society by providing treatment of wastewater for individuals and communities that do not have access to centralized sewage systems. A changing climate, however, reduces the functionality of these systems, contributing to elevated waterborne pathogens and nutrients that are detrimental to human and ecosystem health (Cooper et al. 2016). Especially in coastal areas, OWTS are increasingly at risk of failure due to their vulnerability to increased frequency and intensity of coastal storms, rising sea levels, and rising groundwater tables. These dynamics already take a toll on the systems' ability to treat wastewater, which will continue to be exacerbated in the coming decades (Cox et al. 2019, 2020a,b).

Almost one-half of residents in North Carolina (48%) and South Carolina (40%) rely on OWTS, either individual onsite septic systems or small community cluster systems (EPA 2022). Because much of the Carolina coast is less densely populated, the cost of centralized wastewater treatment can be prohibitive. To be clear, these issues affect inland coastal areas as well as beach communities and barrier islands (Manda et al. 2015).

Building coastal resilience requires place-based planning for resilience and systemic adaptation strategies created with and implemented by wastewater managers. In the last decade, it has become clear that stakeholders such as state and local planners are searching for climate adaptation solutions that comprehensively integrate urban planning, water and wastewater management, and public health into climate adaptation strategies (Allen et al. 2018; Uittenbroek et al. 2013).

While there are general principles to follow for effective climate change adaptation planning and implementation, specific strategies and potential barriers need to be studied sector by sector (Linder and Campbell-Arvai 2021). Limited research has been done specifically on the wastewater sector related to climate adaptation, but the field is growing. A study of centralized wastewater system managers found that many are making changes to build resiliency to storms equivalent to those in the past, but most are not adapting to future climate change (Kirchhoff and Watson 2019). Similar research is needed on the management of decentralized (onsite) wastewater treatment systems, especially for coastal communities that face additional stressors related to climate change such as sea level rise and increasing risk of storm surge (Garner et al. 2017).

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Toward these ends, we seek to better understand the climate change impacts on OWTS by learning from system operators/installers and the health officials who are charged with regulating and permitting these systems. In this study, we interviewed OWTS managers who service and regulate systems in the coastal Carolinas, a region that is particularly vulnerable to climate change (Kunkel et al. 2020). The intent is to catalog the onsite system technologies used, how they function and are regulated, the potential impact of climate change on these systems, and the potential measures that may help coastal communities adapt onsite wastewater infrastructure to changes in climate and weather in the coming decades. We seek to illuminate pathways for coastal municipalities, government entities, and individual households to develop adaptation strategies for OWTS in the face of rising sea levels and changing climate.

2. Background

a. OWTS

OWTS are designed to remove wastewater contaminants and are typically composed of three main parts: a septic tank, a drainfield with trenches, and the soil beneath the drainfield. Primary treatment of wastewater occurs in the septic tank where the biochemical oxygen demand and total suspended solids of the waste are reduced via sedimentation and anaerobic decomposition (EPA 2002). Septic tank effluent is piped to drainfield trenches where the effluent is stored until it infiltrates the soil. Aerobic treatment of the effluent occurs in the trenches and soil if the site conditions are accurately evaluated and the system properly designed. When OWTS are properly sited, designed, and installed they are efficient at reducing the concentration of pathogens, nutrients, and other chemicals found in wastewater (EPA 2022).

The vertical separation distance beneath systems—the depth of the soil treatment area before it reaches groundwater—is one of the most critical standards for ensuring adequate treatment of wastewater (Humphrey et al. 2011, 2017). In South Carolina, a minimum of 15.24 cm of vertical separation is required between the bottom of the drainfield trenches and the seasonal high water table or zone of saturation for most individual OWTS (Department of Health and Environmental Control 2016). In North Carolina, the vertical separation requirement is 30.48 cm for OWTS in coarse loam to clay soils and 45.72 cm for OWTS in sandy soils (North Carolina Office of Administrative Hearings 1956). The elevation of the seasonal high water table is determined on-site by a trained professional who uses a soil auger or soil pits to characterize the morphological properties of the soil, including color, depth, texture, and structure (North Carolina Office of Administrative Hearings 1942). Groundwater level monitoring may be recommended or required for some sites where there is a disagreement with the water table determination based on soil features.

OWTS can tolerate infrequent and brief (a few days) spikes of the water table, causing saturation of the drainfield trenches, whereas prolonged soil saturation results in incomplete treatment of septic effluent (Severson et al. 2008). One of the concerns from the environmental health perspective is the flow of nutrients (i.e., nitrogen and phosphorus) and fecal bacteria, which are discharged from OWTS and may be a significant source of these contaminants in groundwater and surface waters (Iverson et al. 2015; Humphrey et al. 2015). Excess nutrient loads can cause algal blooms, death of aquatic life, and dangers to drinking water in communities nearby (Akpor 2011). Elevated concentrations of nutrients (Humphrey et al. 2015, 2017) and fecal bacteria (Humphrey et al. 2011; Iverson et al. 2017) have been reported in groundwater beneath OWTS and nearby surface waters during periods when water tables were close (<45.72 cm) to drainfield trenches of OWTS.

b. Increasing storm events

Many areas on the East Coast, including North and South Carolina, are experiencing increased frequency and severity of storm events, which are threatening OWTS that are often concentrated in low-lying coastal areas of these states (Allen et al. 2018; Cox et al. 2019, 2020b; Hummel et al. 2018; Kunkel et al. 2020; Little et al. 2015; Miami-Dade County 2018). A recent climate science report for North Carolina finds an increase in the number of observed heavy rainfall events within the state, which are projected to increase in the future as the ocean and atmosphere warms (Kunkel et al. 2020; Easterling et al. 2017). In the Carolinas, weather and climate events have amounted to more than $1.1 trillion in damages since 1980 (NCEI 2020). A deluge of destructive tropical storms and hurricanes have hit the coastal Carolinas in just the past five years, including Hurricanes Matthew (2016), Irma (2017), Florence (2018), and Dorian (2019), signaling a significant increase in storm frequency and severity from the past (Kunkel et al. 2020; Paerl et al. 2019). A study exploring the potential changes in extreme rainfall across eastern North Carolina for 2025–2100 from tropical cyclones found that maximum rainfall intensities could increase by 168% in some areas, and widespread regional rainfall increases could increase up to 44% (Jalowska et al. 2021).

c. Sea level rise

Sea level is also rising within the Carolinas [e.g., +4.62 mm yr^{-1} in the Outer Banks (Duck, North Carolina) from 1978 to 2018 (Kunkel et al. 2020)] and will continue to rise in the future with a projected minimum increase of 152.4 mm for the East Coast by 2100 (IPCC 2019). Sea level rise projections for the Carolinas are more dire than averages for the East Coast as a whole (Piecuch et al. 2018), with important implications for OWTS in those states. In a study using locally adapted scenarios from NOAA's report to the National Climate Assessment (Parris et al. 2012), the authors projected sea level in North Carolina to rise 0.34 m by midcentury and 1.16 m by 2100 using midrange climate "emission" scenarios, with higher levels possible close to the Virginia border (Strauss et al. 2014). The same group projected sea level rise in South Carolina of 0.37 m by 2050 and 1.22 m by 2100, with little

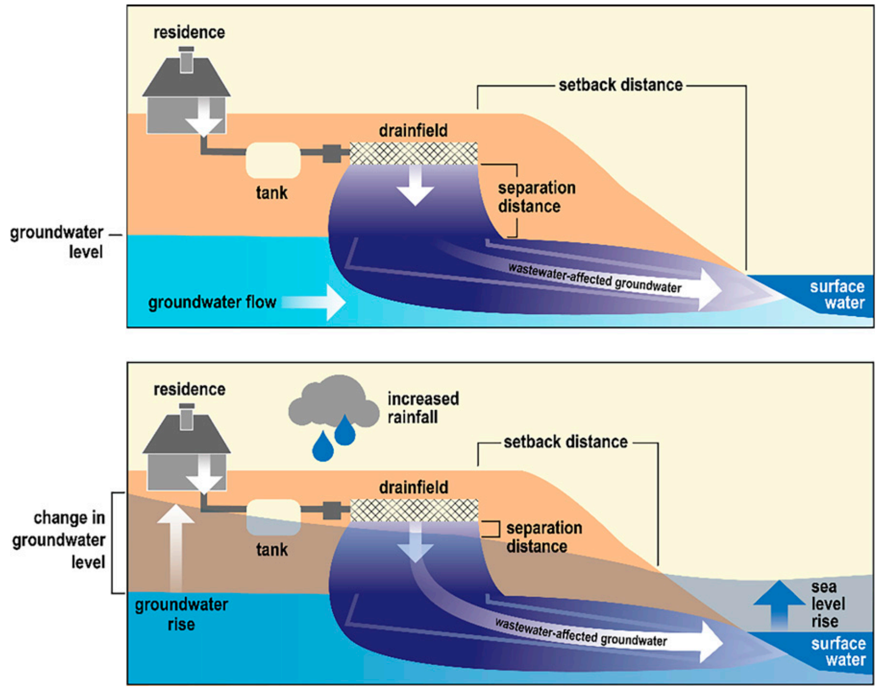

FIG. 1. (top) Normal movement of wastewater through a conventional system for proper treatment, and (bottom) how rising groundwater tables impact wastewater soil treatment areas because of sea level rise and increased rainfall. The reduction in vertical separation distance and horizontal setback distance (distance to surface waters like rivers and estuaries) is depicted in the bottom panel. The illustration is by M. D. Smith (Harrison et al. 2022).

variation within state boundaries (Strauss et al. 2014). Sea level in Charleston, South Carolina, has already risen nearly 2 times as much as the global average (Runkle et al. 2017). We already see the impacts of sea level rise on the North Carolina Outer Banks and South Carolina Low Country in the form of sunny-day flooding (i.e., tidal flooding), which is now a regular occurrence (Kunkel et al. 2020; Reidmiller et al. 2018; Sweet et al. 2018). Low-lying areas in the coastal Carolinas are particularly vulnerable to marine inundation with sea level rise, which tend to be areas that rely on onsite wastewater treatment (Amador et al. 2014; Manda et al. 2015).

Storm events, increased precipitation, rising groundwater tables, and coastal flooding compromise the capacity of soil to treat the septic effluent and remove pathogens (Amador et al. 2014; Cooper et al. 2016; Fisher et al. 2016; Humphrey et al. 2017; Manda et al. 2015; O'Driscoll et al. 2014). North Carolina coastal areas have relatively shallow groundwater depths and high soil permeability rates due to the sandy composition, and as a result, groundwater tables tend to respond quickly to precipitation events and are particularly vulnerable to prolonged flooding (Humphrey and O'Driscoll 2011; Severson et al. 2008). While South Carolina studies have not been conducted to test the responsiveness of groundwater tables to precipitation, similar soil types and groundwater depths are found in both states (Humphrey 2009). With large portions of the Carolinas coastal region lying less than 1.22 m above the high-tide line, the state-level sea level rise projections of 1.16 and 1.22 m, respectively, by 2100, is alarming for the sustainability of coastal infrastructure (Frankson et al. 2017; Runkle et al. 2017; Surging Seas Risk Finder 2022).

d. *Groundwater table rise*

There is evidence that the groundwater table is already rising in many coastal areas along the eastern United States as a result of sea level rise and climate change (Habel et al. 2017; Sweet and Park 2014). From Rhode Island to Miami, Florida, more frequent and longer periods of elevated groundwater are being documented (Cox et al. 2019, 2020a; Miami-Dade County 2018). Coastal groundwater tables can rise between 0.3 and 1 unit of elevation for every unit of sea level rise (Cox et al. 2019; Miami-Dade County 2018). The impact of sea level rise on groundwater table height can be compounded when an imported water supply is artificially recharged to a surficial aquifer, which is common in coastal areas classified as barrier islands (Cox et al. 2019). Higher groundwater tables can result in the narrowing of the vertical extent of unsaturated soil or eliminate it completely, causing saturation of the soil treatment area beneath OWTS, and reducing treatment ability (Cooper et al. 2015; Habel et al. 2017; Hummel et al. 2018; Humphrey et al. 2017) (Fig. 1). Sea level rise, precipitation, community discharge, and geological changes like subsidence are all major factors elevating coastal groundwater tables (Manda et al. 2015; Rahimi et al. 2020).

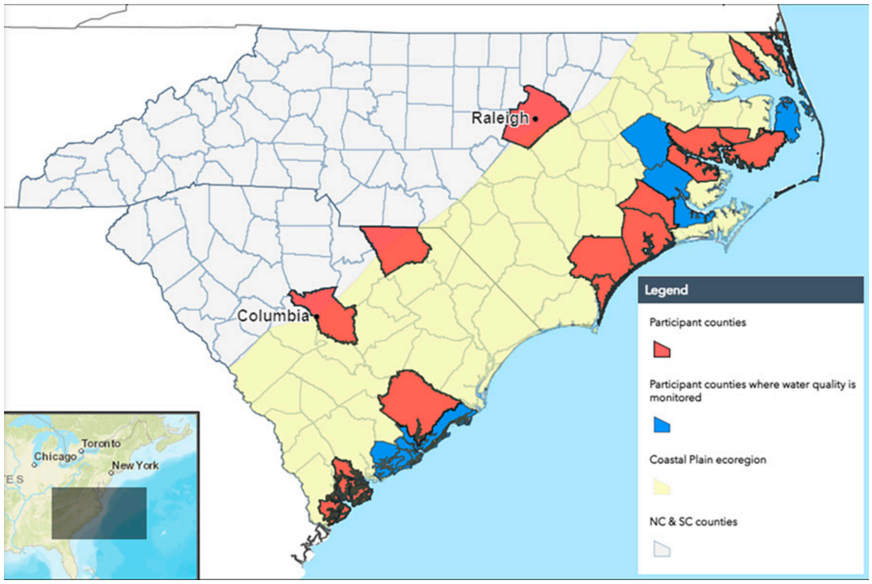

FIG. 2. Participant counties in the Atlantic coastal plain of North and South Carolina.

3. Methods

a. Study area

Our goal was to engage wastewater managers from a cross section of communities in the coastal Carolinas to learn about the status of local OWTS and the implications of climate change. The study area selected for our research was the Atlantic coastal plain delineated by the U.S. Geological Survey (Fig. 2). Counties that overlap with this region were identified for North and South Carolina to create a list of counties applicable to this study. Concurrent research is being conducted on water quality in four of the study counties (Fig. 2).

b. Participants

A total of 28 OWTS managers in coastal Carolina counties voluntarily participated in a semistructured telephone interview composed of open-ended questions related to their professional experience with OWTS in their locale. The group consisted of experts from the private and public sectors: 20 onsite wastewater operators/installers and 8 county and state health regulators.

Wastewater operators/installers are private contractors who install, operate, and repair onsite systems. Operators are state-certified personnel who are tasked with inspecting and maintaining systems, including pumping out the system at a regular interval. Installers, on the other hand, are certified contractors hired to construct, install, repair, or inspect an onsite wastewater system that was designed by a certified engineer. These 20 participants were identified from publicly available lists that provide names and contact information of installers, inspectors, and operators in North and South Carolina. Only those who service the coastal counties of our sample area were eligible to participate. We divided the coastal counties into northern and southern counties within both North and South Carolina. We randomly chose 4–5 potential participants from each of those four regions. In addition, we included three participants (randomly chosen) from each of the four counties (Craven County, North Carolina; Dare County, North Carolina; Pitt County, North Carolina; Charleston County, South Carolina), where long-term water quality research is being conducted with regard to onsite wastewater treatment (C. P. Humphrey and M. A. O'Driscoll 2021, unpublished material).

Health regulators are charged with permitting OWTS and determining which type of onsite system is appropriate for a given property. These eight participants were identified by referrals and snowball sampling (where current participants help recruit future participants for the study) as well as from publicly available lists of environmental health specialists, program managers, and engineers in the two states. Health regulators charged with OWTS permitting and regulations in North Carolina include personnel from county health departments as well as the North Carolina Department of Health and Human Services. Health officials charged with these tasks in South Carolina work for the South Carolina Department of Health and Environmental Control (SCDHEC).

Once potential study participants were identified, we called the professionals to ask if they would be willing to participate in the study. Of the 20 operator/installer respondents, most (14) have 11+ years of experience working with OWTS in the coastal regions of the Carolinas. All 20 operators/installers install, operate, or maintain small-flow ($<$5678.12 L day^{-1}) systems, and nine of those also service large-flow ($>$5678.12 L day^{-1}) systems. Almost all (7 of 8) of the health regulators interviewed have 11 + years of experience. All eight regulators permit small-flow-systems and five of them additionally permit large-flow systems and package treatment plants (PTPs), which are small sewage treatment plants that serve a cluster of homes or businesses.

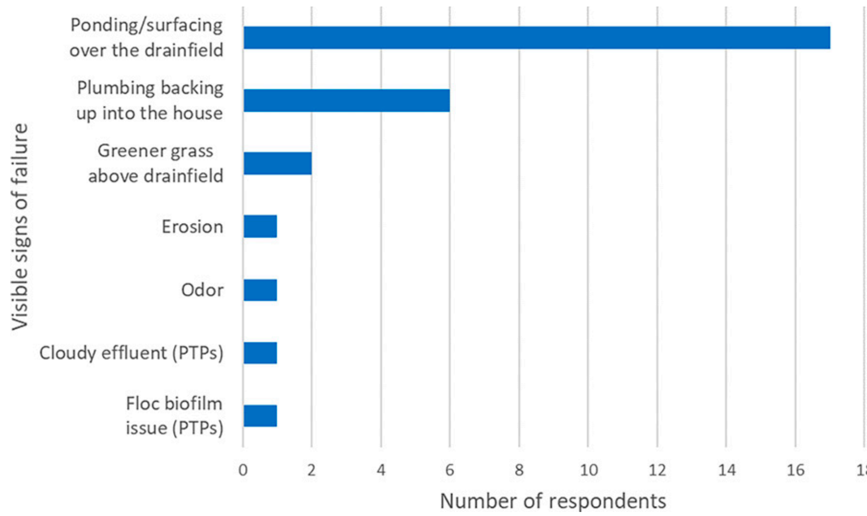

FIG. 3. Number of operators and installers who reported each visible sign of failure in OWTS.

c. *Interviews*

Interview instruments, one for operators/installers and one for health regulators, were designed to determine how these two groups of wastewater managers perceive extreme weather events to affect OWTS and potential adaptation measures. Telephone interviews were conducted between May and November of 2020. Interviews were between 45 and 120 min long and were audio recorded using an external recording device. The interviews were semistructured with open-ended interview questions, which enabled participants to add information they thought would be valuable for the study, such as stories and anecdotes, in addition to giving direct answers to questions asked. All participants gave informed consent prior to participating in the interviews. Interviews were transcribed and analyzed using qualitative techniques of coding to identify, analyze, and summarize key themes (Braun and Clarke 2006).

For operators/installers, the interview instrument asked about site conditions that determine how OWTS handle a heavy rain event or frequent rainfall, visible signs of failure, and the factors that influence system replacement decisions. Three hypothetical weather scenarios were also presented with questions of how a conventional septic system would be expected to respond to the conditions. Participants were asked about impacts of weather-related malfunctions, high groundwater tables and seasonal occupancy on system functionality and life expectancy. They were also asked to describe measures they are using to adapt septic systems to more extreme weather events. Participants were presented with four hypothetical properties in the coastal region and asked to identify an appropriate OWTS for the site and the costs of installation and management. They were also asked about the availability of grants and loans for system replacement and repair in their region.

Health regulators were asked a similar set of questions as the operators and installers but tailored to their role regulating systems in their locality. Interview instruments for both sets of OWTS managers can be found in appendixes A and B.

4. Results

The interviews with coastal Carolina onsite wastewater operators/installers and health regulators provided insight into how they are dealing with current and future climate risks. The information gained from the 28 interviews is discussed in detail below. Although the interview instruments varied some between the two groups (operators/installers versus health regulators), we report on the questions that were asked to both groups (a total of 28 respondents), unless otherwise noted. We refer to both groups together as “wastewater (or OWTS) managers.”

a. *Onsite system functionality and selection*

In the current climate regime, the two groups of wastewater managers interviewed explained that many onsite systems are already at risk of failure. Site conditions in some coastal areas are undesirable, leading to failing systems and constraining development in new areas. Drainage, soil type, elevation, groundwater height, and slope are key to the functionality of OWTS. If an individual system is failing and needs repair or replacement for any reason, including from weather events, the most common visible signs are ponding of septic tank effluent over the drainfield and backing up of plumbing fixtures in the house (Fig. 3). PTPs, which serve a cluster of homes or businesses, may also have cloudy effluent or flocculent (floc) issues (Fig. 3). Floc is a biofilm suspended in the water tank that treats wastewater but can be overwhelmed by excessive volumes of water entering the system. Note that only operators and installers (20 respondents) discussed visible signs of failure.

Determination of which type of system will be installed on a site is done on a case-by-case basis. Factors for determining the type of system to be installed include vertical separation (i.e., the distance between the bottom of the drainfield and the groundwater), soil morphology (i.e., texture, structure, clay mineralogy, organic composition, and presence of constrictive horizons), available space, and horizontal setbacks to water bodies. System installers also consider factors such as lot size and topography, number of bedrooms, and strength of wastewater (i.e., residential strength versus high strength, which is typical of commercial properties).

The onsite wastewater managers interviewed explained that conventional septic systems are the cheapest and simplest option available. Thus, conventional systems are used when possible but are not always appropriate depending on site conditions. There are numerous advanced treatment systems that use additional components and dispersal methods to increase the treatment capacity in cases when conventional systems are insufficient or cannot be accommodated. Advanced treatment options use various methods of treating the contaminants from the wastewater prior to entering the drainfield, such as media filters or disinfection units, or increasing the distance effluent travels through the soil treatment area via pump or mound systems. Such systems are needed when site conditions are considered poor (i.e., when there is limited space on the site for wastewater treatment, the soil and landscape have poor drainage capacity, or the water table is high in that area and is restricting the treatment area). Advanced systems are also often used for sites that have high strength or large quantities of wastewater, such as commercial buildings. Although advanced systems have more potential for treatment of the effluent, they are also more expensive, require periodic inspections, and more maintenance.

Advanced systems are common in the Carolinas and are becoming more so due to declining numbers of sites with ideal conditions for conventional septic systems. One-half of the health regulators interviewed said that limited space is one of the biggest challenges facing OWTS in coastal communities (Fig. 4) because of the rapid growth occurring along the coast and the proximity to surface waters. The largest lots with the best soils have already been developed, so the lots remaining are smaller with less ideal soils. Developers often build the largest house possible for the lot, which results in little space to dispose of wastewater effectively in a septic system. However, more than one-half (5 of 8) of health regulators interviewed reported that rising water table is one of the biggest challenges facing OWTS in coastal communities (Fig. 4). If the water table is too high, it does not allow for the required vertical separation distance between the seasonal high water table and the bottom of the drainfield for proper treatment. The most common problems observed in areas with high groundwater tables are an overall reduction in system function, water backing up into the house, ponding/surfacing water over the drainfield, premature failure, and saltwater intrusion.

During the initial site evaluation, water table height is determined by looking at soil color and morphology and potential flooding conditions are examined via soil texture, which indicates how quickly the soil will drain water and effluent. The required vertical separation distance is determined by the measurement taken on the day of the evaluation. Regulations do not require a buffer for rising groundwater table conditions, but a few inspectors reported that health regulators add a buffer to allow for rising groundwater and for human error during installation.

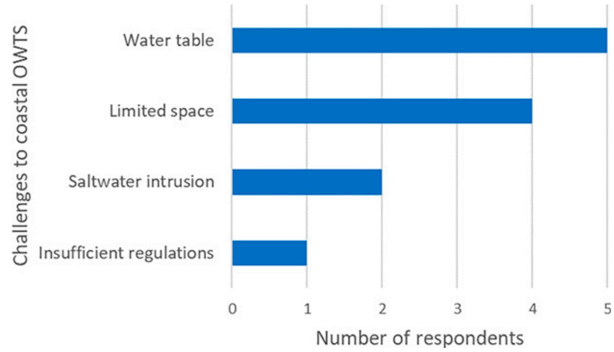

FIG. 4. Top challenges to coastal OWTS as reported by health regulators who were interviewed.

Inspections of conventional septic systems after initial installation are rare, and thus there is scant information available on how these systems are performing before and after disruptive weather events and over time. In North Carolina, conventional systems are not required to be inspected after installation unless there is a problem that needs to be investigated (e.g., odor or ponding water that prompts a complaint), whereas regular inspections are required for advanced systems. Inspection frequency depends on the type of system, ranging from once every 3 months to once every 5 years (North Carolina Office of Administrative Hearings 1961). There are no inspection requirements after installation for conventional or engineered (i.e., advanced) systems in South Carolina (SCDHEC 2019), although it may be possible for towns to pass local ordinances that require inspections circumstantially, such as Folly Beach, South Carolina, has done (City of Folly Beach 2019).

b. *Disruptive weather impacts*

Weather and climate are not directly considered in onsite system approval or site selection, but many of the OWTS managers interviewed are aware of the relationship between weather and climate and the variables they evaluate. Drainage was the number-one site-condition variable respondents mentioned that determines how well a small-flow septic system handles rainfall events (Fig. 5). Drainage is the rate at which a site can dispose of water or drainwater away from the system and allow the dispersal field to dry out. Other important variables impacting how septic systems respond to heavy rainfall are displayed in Fig. 5. Note that only operators/installers (20 respondents) were asked about site-condition variables.

Disruptive weather events can compound the vulnerability of existing less-than-desirable sites. When wastewater operators/installers and health regulators were provided with three hypothetical weather scenarios and asked how they would expect a conventional septic system to handle the conditions, they illustrated how systems are responding to current climate conditions.

In all three scenarios, the hypothetical site experienced an extreme weather event, either a 5-cm rainfall event (first and second scenarios) or an additional high-tide or king-tide event

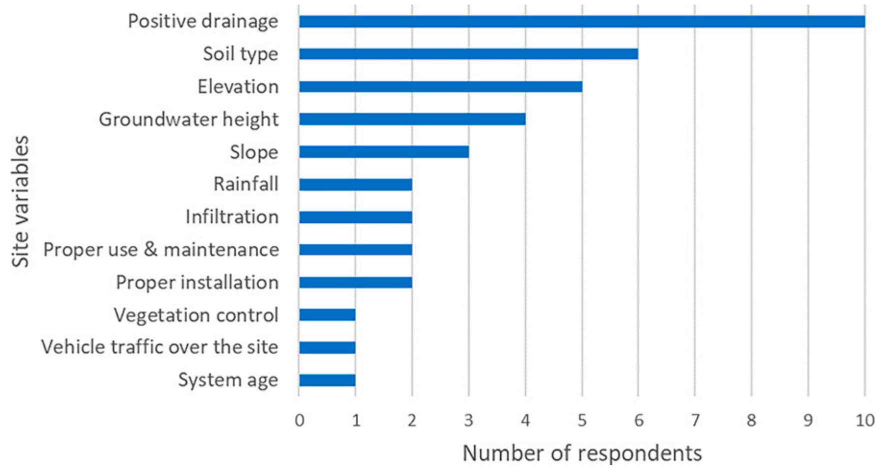

FIG. 5. Site variables that determine how a septic system functions during heavy rainfall.

(third scenario). However, the site in the first scenario had dry soils prior to the event, and the second and third scenarios had saturated soils prior to the event. The majority of respondents said a malfunction *would not* occur with a septic system in the first scenario unless the site had drainage issues prior to the event, but a malfunction *would* occur in the second and third scenarios (Fig. 6), indicating that soil conditions are a critical factor indicating how a system will respond to extreme weather.

If a malfunction occurs in a septic system that is well maintained and does not have any physical damage, operators/installers and health regulators said it would generally be expected to recover on its own or should be given time to "rest" (i.e., a period of no usage). If there is little to no precipitation after the malfunction, recovery usually occurs within a week but can sometimes take up to 14 days, and rarely as many as 30 days. Pumping of the septic tank and distribution box, as well as reduction of water use from the house, can also help the system recover and soils to dry out.

In advanced systems, a weather-related malfunction caused by a hydraulic failure would require the same action to recover as a conventional system: time to "rest." In some cases, the system may need maintenance to regain function because advanced systems have electrical components that would require repair if damaged during a weather event. Advanced systems are generally less likely to malfunction from weather conditions than conventional systems because they are typically designed to withstand adverse conditions, including extreme weather.

In any scenario, participants explained that the following conditions would increase the likelihood of malfunction: prolonged rain for several consecutive days or weeks, high water table conditions, or large downpours of rain of 18–20 cm such as seen during hurricanes. Any system located on a site with poor drainage features is generally more prone to malfunction than one on a well-drained site. Malfunction is more likely in inland areas with clay soils because they have a slower drainage rate. The condition of the septic system also plays a significant role in whether or not a system malfunctions from weather events. If there is an excessively thick biomat (a layer of partially decomposed organic material) building up along

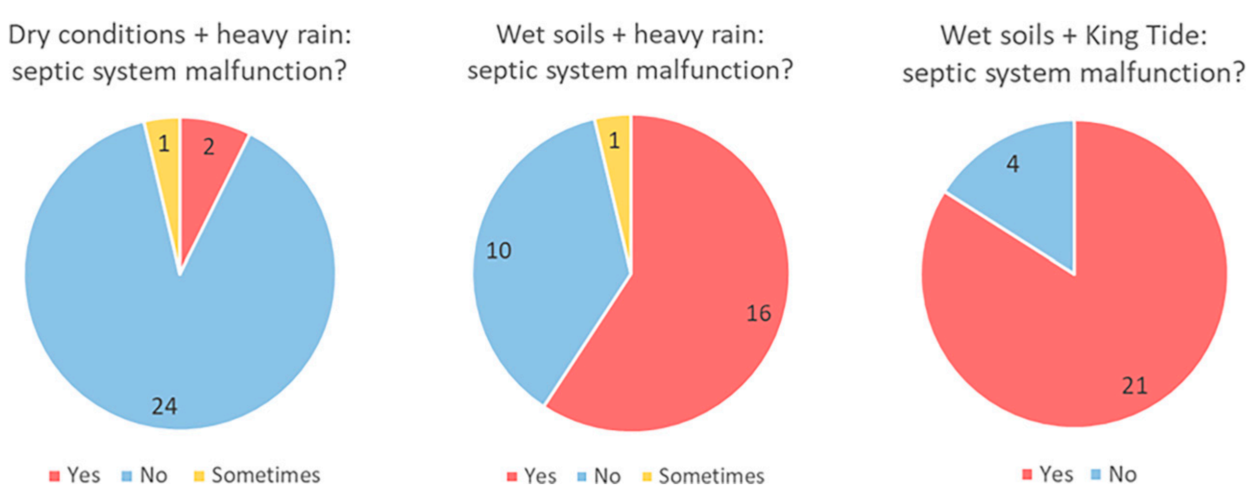

FIG. 6. Septic system malfunction in three hypothetical weather scenarios.

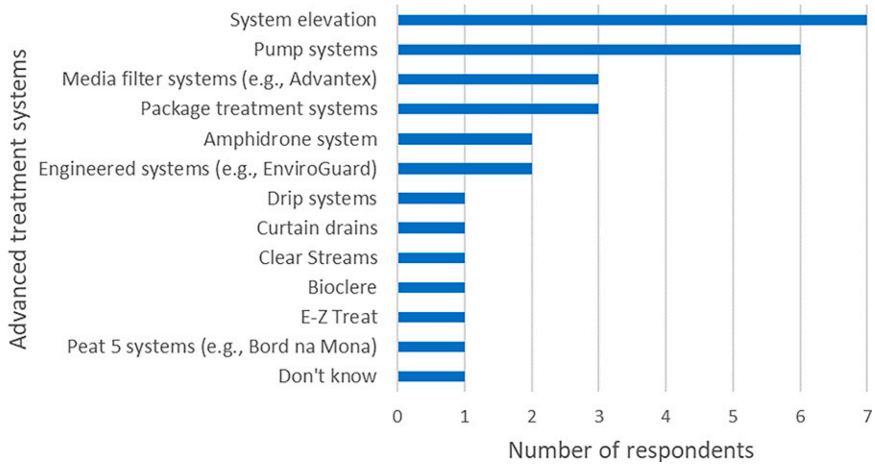

FIG. 7. Recommendations for advanced treatment system options for handling extreme weather.

the drainlines or the system is not maintained properly, the system is more likely to malfunction.

Repeated weather-related malfunctions to septic systems could have a long-term impact on the life of the system and shorten its lifespan if those events result in excessively thick biomat buildup in the drainfield trenches or if the aerobic environment of the soil deteriorates. A reduction in the soil's treatment capacity over time will inevitably lead to system malfunction down the road. However, repeated weather-related malfunctions would not impact the life expectancy of the system if it is able to fully recover after each rainfall or flooding event and does not sustain any physical damage from the event.

c. Adaptation

In the coastal Carolinas, OWTS regulations have not been modified in response to observed changes in frequency and intensity of weather events, yet over half (11 of 17) of operators/installers interviewed reported implementing measures to adapt septic systems to more extreme weather events and rising groundwater levels. The most commonly reported measures by respondents were raising septic tanks and drainfields to be shallower or above ground and recommending various types of advanced treatment systems because they disperse cleaner effluent and some can handle larger volumes of water (Fig. 7). Note that only operators and installers (20 respondents) answered the advanced treatment systems question.

One health regulator said the most important adaptation that could be implemented for onsite wastewater systems would be sustainable management. This would mean an ongoing program in which inspections and maintenance of systems are tracked to ensure systems remain well maintained and compliant with regulations. As it stands currently, older systems are not tracked to ensure continued maintenance and proper functioning. One participant suggested having GPS locations of every private well, public well field, subsurface system, and water treatment plant. This would enable tracking of all existing systems but would require electronic data files for each. Additional municipal and/or health department resources are needed to ensure systems are functioning properly over time, as well as identifying problem areas.

Most health regulators interviewed did not know of any technologies that are meant to address climate change effects on OWTS. The only technological changes mentioned were nontraditional materials used for lining trenches and the use of advanced pretreatment systems. Regulators explained that the need for advanced pretreatment systems is increasing as new construction diminishes the amount of usable land and available sites with adequate soils for septic systems. However, cost is a key limitation for many people to install and maintain advanced systems.

d. Communicating risks

Communications with property owners about regulations and requirements related to their septic systems is limited and inconsistent across the two states. The local or state health department sends the operation permit to owners after a system is installed, which describes and illustrates the system components and their location. Thereafter, communication between regulators and owners varies depending on the local health department and municipality. Some local health departments, such as Craven County, North Carolina, send a North Carolina Cooperative Extension fact sheet on how to maintain a septic system with the operations permit. When a house has a new owner, regulators explained that it is assumed that the previous homeowner provides the new owner with system information. Health regulators reported that some operators and realtors provide a property's septic system information to the new owner, but this practice is not universal.

Regulators explained that local health departments provide OWTS educational materials, but this information must be sought by the homeowner (i.e., via educational websites). For example, publicly available websites (i.e., EPA, local health departments, and university extensions) provide information on how to care for septic systems before, during, and after flooding events. Similarly, flooding risk is not communicated directly to homeowners with septic systems. Some health regulators reported that local health departments do not inform owners of flooding risk of their system at all, while others said there are public service announcements that are sent out before an extreme precipitation event to high-risk areas for potential flooding, informing residents they may be impacted by flood waters. After the event, there are also public service announcements sent out warning people of standing water in the area that could be contaminated by flooded septic systems. However, these announcements are not made to specific residents but to broad zones of potential flooding areas.

There was consensus among participants that education or training opportunities that relate specifically to extreme weather, rising sea levels, and rising groundwater levels are not available to operators/installers or regulators. According to one participant, money for education in the local health departments has run out in recent years, so there are fewer education opportunities in general.

5. Discussion

Our findings suggest the following takeaways about OWTS and climate resilience: (i) weather and climate are important but unaccounted considerations in site approval and system selection, (ii) current regulations are inadequate to deal with future climate risks, (iii) some resilience measures are being implemented regardless of regulations, and (iv) system owners would benefit from additional education and communications to improve adaptive capacity (Fig. 8).

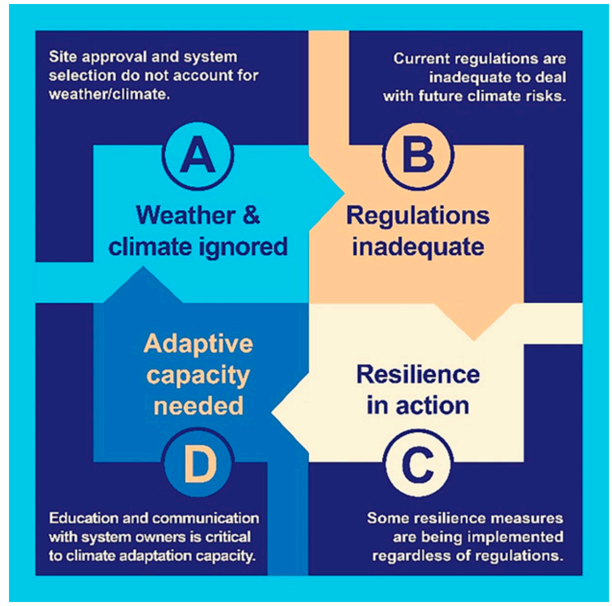

FIG. 8. Four key takeaways from our findings on onsite wastewater treatment and climate resilience. The illustration is by M. D. Smith (Harrison et al. 2022).

a. Weather/climate is ignored

Despite the upward trend of storm frequency and severity in the coastal Carolinas, along with sea level rise observed in low-lying areas of the region, and its negative impacts on OWTS (Paerl et al. 2019; Amador et al. 2014; Manda et al. 2015), weather and climate do not directly impact site approval or system selection. A first step to adaptation is to factor local climate risk science into decisions (Hughes et al. 2021; Kettle et al. 2014; Danilenko et al. 2010), an essential activity missing in the coastal Carolinas. One of the primary influences on whether or not a system will malfunction from climate conditions is the frequency of wetter-than-normal periods (Kohler et al. 2016). Site conditions *combined with* frequency and duration of saturation events would be valuable information to determine system functionality as climate change intensifies. Respondents acknowledged that it would be beneficial for long-term functionality to include some aspects of weather and climate when evaluating sites for installation because, as one operator in Nags Head, North Carolina, stated, “If there are problems [with system functionality], it will be during extreme weather.”

Some participants explained that weather and climate are taken into account in site evaluations *indirectly* through the evaluation of soil conditions, groundwater depth, and horizontal setbacks, as these are all impacted by the season, weather patterns, and time of day within the current climate regime. Future climate shifts will alter groundwater table elevation and the mean high water mark on ocean-side lots, which can affect the setbacks measured at the site evaluation. Measurements taken at the initial site evaluation are insufficient for accounting for weather and climate impacts on the systems in the future. This is not uncommon, as many current water management practices around the world are likely to be inadequate. How we plan and manage water supply, wastewater, sewer, and storm water services require low-regret strategies that consider future climate conditions (Keremane 2015).

b. Regulations are inadequate

Since 2016, the Carolinas have experienced a tropical storm or hurricane every year but one. These storms are likely to become more frequent and severe (Easterling et al. 2017; Jalowska et al. 2021). Despite ample evidence that the climate will be wetter, regulations that promote resilience are slow to follow due to the many barriers and obstacles affecting decision makers (Tryhorn 2010). Previous interview data from centralized wastewater managers revealed that the changes they are making to adapt to past storms was voluntarily initiated, whereas adaptation to future climate change impacts requires regulatory action (Kirchhoff and Watson 2019; Rosenzweig et al. 2007). Our findings suggest a similar conclusion for onsite wastewater management; adaptation to changes in weather and climate are limited by regulations.

When discussing technologies that improve the function of OWTS in extreme weather, a Pitt County operator said “It doesn’t really matter what systems could improve it . . . if it’s not state-approved by North Carolina, it doesn’t matter—you can’t use it . . . Technology is growing, but yet we’re using a four-decade old rulebook. So, basically, our hands are tied.” Dated regulations hinder adoption of technological advancements. Although new technologies are available that are proving to be more robust and sustainable, these more resilient systems must be required by regulations for them to become widespread.

Our findings suggest that municipalities and health departments in the coastal Carolinas lack sustainable programs to assist owners with proper system operation. If our study area in the Global North—communities in a developed country with relative wealth—is not able to manage the normal maintenance needs for wastewater infrastructure, these findings do not bode well for even-more-resource-limited communities tackling climate adaptation. Urban areas in the Global North like New York City and Miami, and even smaller cities like Saint Augustine, Florida, have begun to institute climate change considerations in wastewater infrastructure planning (Rosenzweig et al. 2007; Miami-Dade County 2018; Kyzar 2021), but many less resourced communities in the United States are still behind. A North Carolina state health regulator explained that "a number of counties do not have a robust inspection program . . . health department staff are notoriously underfunded and overworked." Additional capabilities for tracking systems would be needed to ensure systems are functioning properly over time, and that requires resources that may not be available or feasible within the current regulatory structure or within county or state budgets.

Regulations also vary at the state level, which presents additional challenges to improving how OWTS are monitored and maintained within communities. OWTS are regulated under state law, but neither North nor South Carolina have developed regulatory frameworks that specifically address climate change impacts on septic systems (Harrison et al. 2022). Coastal local governments must cope with the repercussions of climate change on the septic systems in their communities, so the question becomes if they are permitted to take regulatory actions under state law. For example, North Carolina statute prohibits local regulation of septic systems, so coastal communities risk being sued and regulations being struck down if they take regulatory action in their locality. South Carolina, on the other hand, does not have any such prohibition, so local communities may initiate local requirements for septic systems (Harrison et al. 2022). However, South Carolina has information gaps in their regulations that create other barriers. One such information gap has resulted in a practice in Folly Beach of destroying all septic permits that were issued more than five years ago. As a result, an inventory of every septic system within the community must be performed before making a decision between updating and regulating OWTS or replacing all OWTS with sewer service in the community (Harrison et al. 2022).

c. *Resilience in action*

While regulations may limit the advancement of OWTS technological innovations for climate adaptation, there is evidence that many OWTS installers and health regulators are initiating changes to improve OWTS functionality in response to recent changes in weather and soil conditions. Some system installers are being more conservative during installation by adding drainlines in the drainfield or using a larger septic tank, for example. Other system installers are installing more-elevated systems. Such actions are generally being done by installers out of reaction to past disruptive weather events in an attempt to maintain capacity of the systems in similar events. Reactive adaptation measures contribute to resilience and are a type of climate adaptation defined as actions that moderate harm from the climate risks a locality has experienced or are currently experiencing, in contrast to proactive measures that "exploit beneficial opportunities" to plan for future climate impacts (Linder and Campell-Arvai 2021; IPCC 2018). Wastewater managers are planning for storm events similar to what has been experienced to date. Our findings echo the results of a study of centralized wastewater treatment system managers who are making changes to build resilience to storms they have experienced in the past but not adapting to future climate change (Kirchhoff and Watson 2019).

Many other adaptive measures exist and are becoming increasingly popular around the globe because of rising environmental and climatic concerns. For example, various types of biological wastewater treatments methods have shown promise to providing low-energy, low-cost and efficient means of treating domestic wastewater (Manyuchi et al. 2019; Singh et al. 2019). Biological wastewater treatments include green plant-based technologies such as phytoremediation, constructed wetlands, and algal pond systems; these treatments have been successfully used in many locations around the world, including California and India (Singh et al. 2019). Another biological wastewater treatment is vermifiltration, which is the process of using earthworms and aerobic bacteria to treat wastewater. Case studies in India and Zimbabwe have shown such biological technologies can significantly reduce contaminants (i.e., metals and nutrients) from wastewater (Manyuchi et al. 2019; Singh et al. 2019). Implementation of wastewater reuse systems is another environmental protection measure that can significantly reduce the amount of contaminants released into the surrounding environment (Azam et al. 2019; Tripathi et al. 2019).

Monitoring technology that allows for real time evaluation of system functionality, such as sensors, data communication and data handling, can also be useful to determine performance of wastewater infrastructure over time (Singh and Tiwari 2019). Electronic GIS datasets can be used to track septic systems in a locality—indicating where septic systems are located, or inadequate, and what areas are at risk of rising groundwater and sea levels, etc. The Georgia Department of Public Health has instituted such a program to provide a web-based method for tracking private well and sewage treatment installation data (Southern Georgia Regional Commission 2020). These types of adaptive measures have great promise but require alignment with regulations (Manyuchi et al. 2019), as well as education of OWTS managers and technology availability.

As already noted, resiliency planning for wastewater infrastructure is occurring in better resourced communities in the United States. Nags Head, a relatively prosperous coastal community, has a Septic Health Initiative that provides free septic system inspections, septic system pump outs, water utility bill credits, low-interest loans for septic system repairs or replacement, and water quality testing (Miller 2022). A recent update to their decentralized wastewater management plan details how the town will expand and improve the program to confront increasing sea level and storm activity impacting on-site functionality (Miller 2022). New York City developed a climate risk management framework for strategic and capital planning of their water systems (Rosenzweig et al. 2007). Miami-Dade County and Saint Augustine in Florida have both completed comprehensive vulnerability assessments of the impacts of climate change on the OWTS in their locality (Miami-Dade County 2018). These communities are on the frontlines of OWTS adaptation to climate change in the United States, providing insight into the types of actions coastal communities can take in order to implement climate resiliency planning for wastewater infrastructure.

d. *Adaptive capacity needed*

While improving the resilience of wastewater treatment systems to contend with recent storms is laudable, adapting to the past is not likely to provide protection from future climate risks. Increasing adaptive capacity of municipalities to deal with climate change impacts is a key strategy for more effective wastewater treatment (Singh and Tiwari 2019). Improvement of communications and increased education are concrete, feasible actions that contribute to climate adaptation capacity. Prior research shows that effective communication with the public and education with wastewater managers are essential to implementing and strengthening climate adaptation measures in the infrastructure sector (Jiricka-Purrer et al. 2018; Rudberg et al. 2012; National Science and Technology Council 2012).

Communication with property owners about OWTS is fractured and inconsistent, contributing to system malfunction in our study area. Communications about regulations and requirements occur with the initial installation of a septic system and receipt of the system permit. However, homeowners do not receive consistent information about indicators of system failure nor when maintenance may be needed (e.g., green grass growing over the drainfield, slow plumbing in the house). Implementation of consistent communication of system information to all new homeowners, including when a property is purchased by a new owner, could significantly improve owner awareness of how to properly maintain the system at their home. Municipalities, for example, have a role to play in educating their residents, like the Town of Nags Head, which maintains a septic health program and provides such informational services to property owners (Town of Nags Head 2021).

Ample educational resources about maintenance of OWTS are available on local health department, university extension, and Environmental Protection Agency websites but are rarely provided directly to system owners. Plus, this information is not targeted toward coastal communities dealing with sea level rise, groundwater rise, and coastal flooding. In addition, if a homeowner needs information on system requirements or maintenance after installation, it is up to the individual to seek that information out, for instance, by calling the state or local health department or searching for answers online. For example, conventional systems are recommended to be pumped every 3–5 years, but not all homeowners receive this guidance. The scarcity of direct communication between septic regulators and homeowners may play a significant role in why older systems are not properly maintained.

Communication between local and state agencies (i.e., emergency management agencies, public health agencies, meteorological services) and residents of those communities is crucial during times of extreme weather-related emergencies (Potter et al. 2021; Hawkins et al. 2017). Recent research on impact-based forecast and warning systems is promising, with implications for flood risk communications about OWTS. These early warning systems include specific social, economic, and environmental impacts of a hazard and allow residents to prepare for the consequences of the hazard (WMO 2015). Impact-based systems have been found to increase the public's understanding of an impending hazard and the potential impacts of it and improve interagency communication, which is key during the warning, response, and recovery phases of an extreme event (Potter et al. 2021; Uccellini and Ten Hoeve 2019). Use of these types of impact-based warning systems with septic system owners prior to a flooding event would ensure that vulnerable residents receive direct and consistent information about how to prepare for the impacts to their system and respond accordingly, for example, minimizing or halting the use of plumbing in the house for 48 h after an event. Note that some of the adaptation approaches associated with dealing with flooding coastal systems may also be relevant for inland communities that are located near floodplains and/or are experiencing increasing rainfall intensity.

The operators and installers who work directly with OWTS are another untapped resource for communicating with system owners. Educating operators, installers, and regulators about the increasing challenges for onsite systems from disruptive weather events as well as options for adaptation measures could improve communication with owners and potentially ensure widespread awareness and consistent strategies. Researchers and university extension professionals are well suited for distributing such outreach materials and educating both types of OWTS managers on climate adaptation (Linder and Campbell-Arvai 2021). North Carolina Cooperative Extension offered their first continuing education program on these topics in 2021 (Severson 2021). We are not aware of any such educational opportunities in South Carolina.

6. Conclusions and recommendations

This study advances what we know about on-the-ground implementation of OWTS function and management in the current climate and what operators, installers, and health regulators are doing to adapt to extreme weather in the coastal Carolinas. The results are intended to provide communities, government officials, and OWTS managers in North and South Carolina with information to help guide system adaptation and resiliency planning in the coming years.

More work is needed to systematically test how OWTS perform under different weather scenarios, and our study complements research being conducted to do just that in various locations along the Carolina coast (Harrison et al. 2022).

While this study explored onsite wastewater managers' perceptions of the impacts of extreme weather on onsite systems, it may also be useful to examine OWTS managers' understanding of and beliefs around climate change (e.g., belief in its occurrence, causality, immediacy of impacts, and potential barriers to the implementation of adaptation strategies). Continued work is also needed to explore OWTS adaptation from various regions to apply lessons learned from locale to locale. A recent assessment of OWTS vulnerability to sea level rise and storm surge in Saint Augustine is an example of the type of comprehensive analysis that is needed in coastal communities across the United States, particularly those with high concentrations of residents with septic systems (Kyzar 2021). Valuable insights were gained from wastewater professionals in our study area, but further insights may be gained by evaluating barriers experienced by system owners and their perceptions and willingness to adapt, as well as exploring issues faced by inland communities. Many of the adaptation approaches associated with coastal systems may also be relevant for inland communities that are located near floodplains and/or experiencing increasing rainfall intensity.

Resources available for OWTS adaptation vary by state, as does the degree of fragmentation and cohesion of regulation and communication at local and state levels. To account for this variability, comprehensive outreach programs pertaining to adaptation of OWTS issues are needed to convey pertinent information to coastal communities and increase adaptive capacity, targeting private sector operators/installers, health regulators, municipalities, and household decision makers. Onsite wastewater education programs must become more widespread to inform policy/decision-makers about OWTS functionality in a changing climate.

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Data availability statement. Because of confidentiality agreements, supporting data can only be made available to bona fide researchers subject to a nondisclosure agreement. Details of the data and how to request access are available from author Jane Harrison (jane_harrison@ncsu.edu) at North Carolina Sea Grant, North Carolina State University.

APPENDIX A

Operator/Installer Interview Instrument

Appendix A provides the questions asked of each operator and installer participant during the phone interviews in this study. The interviews were semistructured, and thus allowed for stories, anecdotes, and other voluntary information provided by the respondents.

Section I: Introduction

1) What site variables determine how well an onsite wastewater treatment system functions during heavy rainfall events?
   a) What site variables determine how well a system functions during frequent rainfall events (continual saturation)?
   b) What are the visible signs of failure during sporadic heavy rain or continual saturation?
   c) How does seasonal occupancy impact the functioning of a septic system at a vacation home site?
2) How is a system determined to need replacement?

Example 1: Imagine that there have been dry conditions for a while, enough time to create very dry soils. After that time, there is an intense rainfall event that produces 2 inches of rain in one day.

3) Would you expect a conventional system (septic tank + gravel trench/drainfield) to malfunction or experience treatment failure in these conditions? Yes No
   a) If yes, how long after the event would it take for the system to recover? Please give a typical range of days/weeks.
   b) If not, under what rainfall conditions would you expect it to malfunction?
4) What maintenance would be needed to regain functionality after a heavy rain event like the one in this example?
   a) How do conventional systems (septic tank + drainfield) compare to advanced systems (that include pretreatment components) in terms of what is required to regain functionality? Please refer to the reference handout provided for a list of advanced systems.
   b) How do individual/small-flow septic systems compare to package treatment plants/large-flow systems in terms of what is required to regain functionality?

Example 2: Now imagine an inland coastal area that is more than 1 mile from the ocean. Soils are currently saturated from prior rainfall. Then there is a heavy rainfall event that produces 2 inches of rain in one day.

5) Would you expect a conventional system to malfunction or experience treatment failure in these conditions? Yes No
   a) If yes, how long after the event would it take for the system to recover? Please give a typical range of days/weeks.
   b) If not, under what rainfall conditions would you expect it to malfunction?
6) What maintenance would be needed to regain functionality after a heavy rain event like the one in this example?

Example 3: In this last scenario, imagine a coastal area within 1 mile of the ocean. Soils are currently saturated from prior rainfall. Simultaneously, the area is experiencing a high/king tide event, causing an exceptionally high tide 12 inches above the average high tide.

7) Would you expect a conventional system to malfunction or experience treatment failure in these conditions? Yes No
   a) If yes, how long after the event would it take for the system to recover? Please give a typical range of days/weeks.
   b) If not, under what high tide or storm surge conditions would you expect it to malfunction?
8) What maintenance would be needed to regain functionality after a high tide event or storm surge like the one in this example?
9) How would system malfunctions caused by extreme weather events such as these impact the life expectancy of a system?
10) In low-lying areas where the groundwater table is shallow, do you notice more problems with onsite system functionality? Yes No
    a) If yes, what types of problems?
    b) Are these problems typically event-based, occurring for several days after major precipitation events (>2 inches) or are they chronic problems that occur for longer durations (>several days)?

Section II: Adaptation strategies to hazards posed

11) Are you currently taking any measures to adapt onsite wastewater treatment system operation or installation to weather extremes, sea level changes, and/or shallower water table conditions (which is related to increased groundwater depths)? Yes No
    a) If so, what are you doing?
    b) If so, what prompted the change/action?
12) Can you tell me about septic or package plant technology changes that could improve their functionality during extreme weather, higher sea level, and/or shallower water table conditions?
13) Which advanced treatment systems would you recommend for handling extreme weather events like the examples we discussed earlier? Please refer to your reference handout for a list of advanced treatment systems.
    a) Under what conditions would you recommend these?

Section III: What are the costs?

Example 1: Imagine a property that is a standard home: 2000 square feet, 4 bedrooms, 2.5 bathrooms on a 1/4 acre lot. The soils have a good percolation rate, requiring a 480 square foot drainfield (3 trenches, each 3 ft × 53 ft).

14) What type of system would you expect to install for this home?
15) What would be the approximate installation cost, including the system, drainfield, and labor?
16) What would be the approximate maintenance/operational cost of that system each year?

Example 2: Next imagine a property that is a vacation home with heavy seasonal occupancy between May and September: 4000 square feet, 8 bedrooms, 7 bathrooms on a 1/2 acre lot. The soils have a good percolation rate, requiring a 960 square foot drainfield (4 trenches, each 3ft × 80 ft).

17) What type of system would you expect to install for this home?
18) What would be the approximate installation cost, including the system, drainfield, and labor?
19) What would be the approximate maintenance/operational cost of that system each year?

Example 3: Now imagine a property that is a commercial building: an office building with an average sewage wastewater flow of 1200 gallons per day. The wastewater is high-strength.

20) What type of system would you expect to install for this type of commercial property?
21) What would be the approximate installation cost, including the system, drainfield, and labor?
22) What would be the approximate maintenance/operational cost of that system each year?

Example 4: Finally, imagine a housing development with 100 homes and an average sewage wastewater flow of 45,000 gallons/day. You have been asked to install a package treatment plant to serve as a neighborhood-scale wastewater treatment facility.

23) What type of advanced treatment components would you expect to include in the installation of a package treatment plant like the one in this example? Please refer to your reference handout (pg. 2) for examples of advanced treatment components for large-flow (>1,500 gal/day) systems.
24) What would be the approximate installation cost of the facility, including the systems, drainfield, and labor?
25) What would be the approximate maintenance/operational cost of that system each year?
    a) What would be the approximate cost to each homeowner connected to the treatment facility each year?
26) What would be the approximate cost to add a pretreatment component/technology to a site that already has a system installed? You may choose one type of pretreatment to use as an example. Refer to the reference handout for a list of common pretreatments.
    a) How would the cost of that pretreatment addition compare to the cost of including the same type of pretreatment in the initial installation of the system? What would be the difference in cost?
27) What are the public financing options (grants or loans) available to build or repair individual/small-flow onsite wastewater treatment systems?
28) What are the public financing options (grants or loans) available to build or repair package treatment plants/large-flow onsite wastewater treatment systems?

APPENDIX B

Health Regulator Interview Instrument

Appendix B provides the questions asked of each health regulator participant during the phone interviews in this study. The interviews were semistructured, and thus allowed for stories, anecdotes, and other voluntary information provided by the respondents.

Section I: Introduction

1) What is your current position title and organization where you work?
2) In your current position, do you work at the county or state level? Which county/state? County __________State ____________
3) Do you regulate or play a role in the installation, operation, or maintenance of small-flow (<1,500 gallons per day) onsite wastewater treatment systems? Yes No
   - If yes, how many years of experience do you have regulating small-flow onsite wastewater treatment systems? Less than 2 years 2–5 years 6–10 years 11–20 years 21+ years
4) Do you regulate or play a role in the installation, operation, or maintenance of large-flow (>1,500 gallons/day) systems, including package plants? Yes No
   - If yes, how many years of experience do you have regulating small-flow and/or large-flow systems? Less than 2 years 2–5 years 6–10 years 11–20 years 21+ years
5) In what regions of coastal North/South Carolina are the septic systems and/or package plants that you regulate? Check all that apply.
   ❏ Sandhills
   ❏ Inner Coastal Plains
   ❏ Outer Coastal Plains
   ❏ Estuarine/Inner Banks
   ❏ Outer Banks
6) How many years of experience do you have regulating onsite wastewater treatment systems in the coastal regions of North or South Carolina? Less than 2 years 2–5 years 6–10 years 11–20 years 21+ years
7) Based on your experience, what do you see as the biggest challenge for onsite wastewater treatment systems in coastal communities?

Section II: Catalog existing onsite wastewater technology regulation

8) Before issuing a permit for an onsite wastewater treatment system installation, how is it determined what type of system will be installed at a given site?
   a) How do environmental factors impact system design and site requirements (e.g., distance from surface waters, distance from protected habitat, etc.)?
   b) What role do you play in making these permitting decisions?
9) What would you say is a typical/average depth to the groundwater table at the coastal sites where you are permitting septic installations? What is a typical range?
10) How common is it for advanced or engineered systems to be recommended or needed at coastal sites? Not common at all Common Very common Do not know
    a) Under what site conditions are these recommended?
11) Do you play a role in inspecting onsite wastewater treatment systems at any time before, during or after installation? Yes No
    a) If yes, describe.
    b) What happens if a system fails inspection?
12) Are property owners required to have existing septic systems regularly inspected in your locality?
    a) If yes, what are the legal/regulatory repercussions for property owners who do not maintain their system properly to avoid malfunction? Consider both surface malfunctions and subsurface malfunctions.
13) How are regulatory conditions and local/state requirements for a septic system communicated to property owners? (Clarifying, if needed: are there communications sent to property owners to notify them of upcoming inspections, maintenance requirements, etc.?)
14) Are there different permitting requirements or special considerations made for septic installations at coastal vacation homes where there will be significant seasonal fluctuations in load to the septic system? Yes No
    a) If yes, what are the differences?
15) How do permitting requirements differ for package plant systems compared to individual septic systems?
16) For systems that reuse wastewater using spray or drip irrigation, is the irrigate tested for contamination on a regular basis? Yes No
    a) If so, how often?
    b) Under what circumstances is spray or drip irrigation used at a site?
    c) Do you play a role in ensuring people or animals don't come in direct contact with the effluent?
       (i) If so, how?

Section III: Perceived vulnerabilities of septic systems to climate

17) We were talking earlier about what kinds of site conditions go into determining the type of system installed. How does weather and climate go into making a site decision?
    a) Is flooding risk included in making a site decision?
    b) Is the water table height after heavy rain events included in making a site decision?
18) Do the current requirements for drainfield depth provide any buffer for rising groundwater tables?
19) Does the county health department inform system owners of immediate or potential flooding risk of their systems? Yes No
    a) If yes, how are owners informed of the flooding risk? Please differentiate between immediate and potential flooding risk in your communications.

b) If not, what would be needed to be able to provide timely advice to system owners before, during, or after a flooding event (online resources, etc.)?

20) Are there any methods of flood forecasting used for onsite wastewater treatment system decision-making (e.g., FEMA flood maps, etc.)? Yes No
a) If yes, how are they used?

21) Have regulations or regulatory decisions changed in response to any perceived change in frequency or intensity of weather events over time? Yes No
a) If yes, describe any changes you have noticed.
b) If yes, what have you noticed in terms of weather event impacts on functioning of onsite wastewater treatment systems over time?

22) Do you receive higher numbers of malfunction complaints or applications for repair permits for individual septic systems after an extreme weather event? Yes No
a) If yes, please describe the weather conditions.
b) If yes, what happened/what was the impact on septic systems?

Example 1: Imagine that there have been dry conditions for a while, enough time to create very dry soils. After that time, there is an intense rainfall event that produces 2 inches of rain in one day.

23) Would you expect a conventional system (septic tank + gravel trench/drainfield) to malfunction or experience treatment failure in these conditions? Yes No
a) If yes, how long after the event would it take for the system to recover? Please give a typical range of days/weeks.
b) If not, under what rainfall conditions would you expect it to malfunction?

24) What maintenance would be needed to regain functionality after a heavy rain event like the one in this example?
a) How do conventional systems (septic tank + drainfield) compare to advanced systems (that include pretreatment components) in terms of what is required to regain functionality? Please refer to the reference handout provided for a list of advanced systems.
b) How do individual/small-flow septic systems compare to package treatment plants/large-flow systems in terms of what is required to regain functionality?

Example 2: Now imagine an inland coastal area that is more than 1 mile from the ocean. Soils are currently saturated from prior rainfall. Then there is a heavy rainfall event that produces 2 inches of rain in one day.

25) Would you expect a conventional system to malfunction or experience treatment failure in these conditions? Yes No
c) If yes, how long after the event would it take for the system to recover? Please give a typical range of days/weeks.
d) If not, under what rainfall conditions would you expect it to malfunction?

26) What maintenance would be needed to regain functionality after a heavy rain event like the one in this example?

Example 3: In this last scenario, imagine a coastal area within 1 mile of the ocean. Soils are currently saturated from prior rainfall. Simultaneously, the area is experiencing a high/king tide event, causing an exceptionally high tide 12 inches above the average high tide.

27) Would you expect a conventional system to malfunction or experience treatment failure in these conditions? Yes No
e) If yes, how long after the event would it take for the system to recover? Please give a typical range of days/weeks.
f) If not, under what high tide or storm surge conditions would you expect it to malfunction?

28) What maintenance would be needed to regain functionality after a high tide event or storm surge like the one in this example?

29) How would system malfunctions caused by extreme weather events such as these impact the life expectancy of a system?

30) In low-lying areas where the groundwater table is shallow, do you notice more problems with onsite system functionality? Yes No
g) If yes, what types of problems? Consider both surface and subsurface problems.
h) Are these problems typically event-based, occurring for several days after major precipitation events (>2 inches) or are they chronic problems that occur for longer durations (>several days)?

Section IV: Adaptation strategies to hazards posed

31) Do current regulatory requirements include measures to adapt onsite wastewater treatment system operation or installation to weather extremes, sea level changes, groundwater salinity changes, and/or shallower water table conditions? Yes No
a) If yes, what measures or adaptations are currently being used?
b) If yes, what prompted the change/action?

32) What are leaders in the onsite wastewater sector, both private and public entities, doing to adapt to weather extremes and climate change, if anything?

33) Which technologies and siting strategies are improving onsite wastewater treatment system function during extreme weather or considering climate change?
a) What are the limitations to these technologies and siting strategies?

34) Are you using any weather or climate data/tools related to onsite wastewater treatment system planning and/or decision-making? Yes No

a) If you are using data/tools, which data/tools are you using?
b) How are you using the data/tools?
c) What recommendations, if any, would improve the accessibility and use of the data/tools?
d) If you are not using weather or climate data/tools, are you aware that climate tools exist that show coastal flooding projections? Yes No
   (i) Do you see any benefits in having climate/weather data for use in onsite wastewater treatment system planning? Yes No
   (ii) Would you know where to go/who to contact for this information? Yes No

35) What public education or training options are available for property owners with onsite wastewater treatment technologies to learn about maintenance needs to prevent system malfunction in the face of extreme weather, rising sea levels, and rising groundwater levels?
36) What education or training options are available for septic system installers/operators to learn about taking sea level rise, increasing groundwater tables, and flooding into consideration when making site decisions?

Section V: What are the costs?

37) What are the public financing options (grants or loans) available to build or repair individual/small-flow onsite wastewater treatment systems?
38) What are the public financing options (grants or loans) available to build or repair package treatment plants/large-flow onsite wastewater treatment systems?

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