2019 Edition

Susceptibility of Public Health Impacts from Flooded Water, Wastewater and Public Health Infrastructure

Guidebook for Community Level Assessment

Sea Grant | S.C. SEA GRANT CONSORTIUM
Coastal Science Serving South Carolina

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Table of Contents

INTRODUCTION

ISSUE FRAMING

APPROACH

CONCLUSION

About the Guidebook

This guidebook was made possible through support to the South Carolina Sea Grant Consortium from the National Oceanic and Atmospheric Administration's Coastal and Ocean Climate Applications (COCA) program, aimed at addressing the needs of decision-makers grappling with pressing climate-related issues in coastal and marine environments. The project team consisted of scientists, outreach specialists and graduate students from South Carolina Sea Grant Consortium, North Carolina Sea Grant at North Carolina State University, East Carolina University, Old Dominion University, Virginia Tech, Saint Louis University, Medical University of South Carolina (MUSC), College of Charleston, and the Carolinas Integrated Sciences and Assessments (CISA). This publication was sponsored by the South Carolina Sea Grant Consortium pursuant to National Oceanic and Atmospheric Administration award number NA15OAR4310111.

The project goal was to improve the resiliency of coastal communities by developing an assessment tool to identify weaknesses in public health infrastructure – specifically water, wastewater and access to health care facilities – to flooding, and to locate resources to reduce susceptibility to public health disasters.

The project team is most grateful for the time and expertise provided by other participating organizations, including MUSC Emergency Management, City of Charleston, S.C. Emergency Management, College of Charleston Emergency Management, Charleston County Emergency Management, Coastal Conservation League, City of Charleston Council, City of Charleston Geographic Information Systems, City of Charleston Public Service, City of Charleston Planning, Charleston Water System, James Island Public Service District, Charleston County Zoning and Planning Department, Charleston Waterkeeper, S.C. Hospital Association, Roper St. Francis Hospital, S.C. Department of Health and Environmental Control (SCDHEC) Office of Ocean and Coastal Resource Management, SCDHEC Office of Public Health Preparedness, SCDHEC Bureau of Water, Town of Morehead City, N.C., Town of Newport, N.C., and NOAA National Weather Service.

Summary

Using an operational environmental impact health assessment format (Briggs, 2008, Figure 1), the purpose of this project was to develop a method of assessing the resilience of public water and wastewater systems to flooding as well as the access to health care facilities, and

therefore to improve the health outcomes of communities when faced with tropical storms, increased tidal flooding, and extreme rain events. Using a simple model of Susceptibility=Vulnerability-Resilience, we developed resources and tools needed to help communities lower their susceptibility to the public health impacts from these events.

Two cities – Morehead City, N.C. and Charleston, S.C. – were selected to develop the tool based on their desire to lessen impacts from flooding, their differences in size and geomorphology, and the engagement of the two state Sea Grant programs and CISA with community partners. Community members such as hospital, municipal, county and local emergency

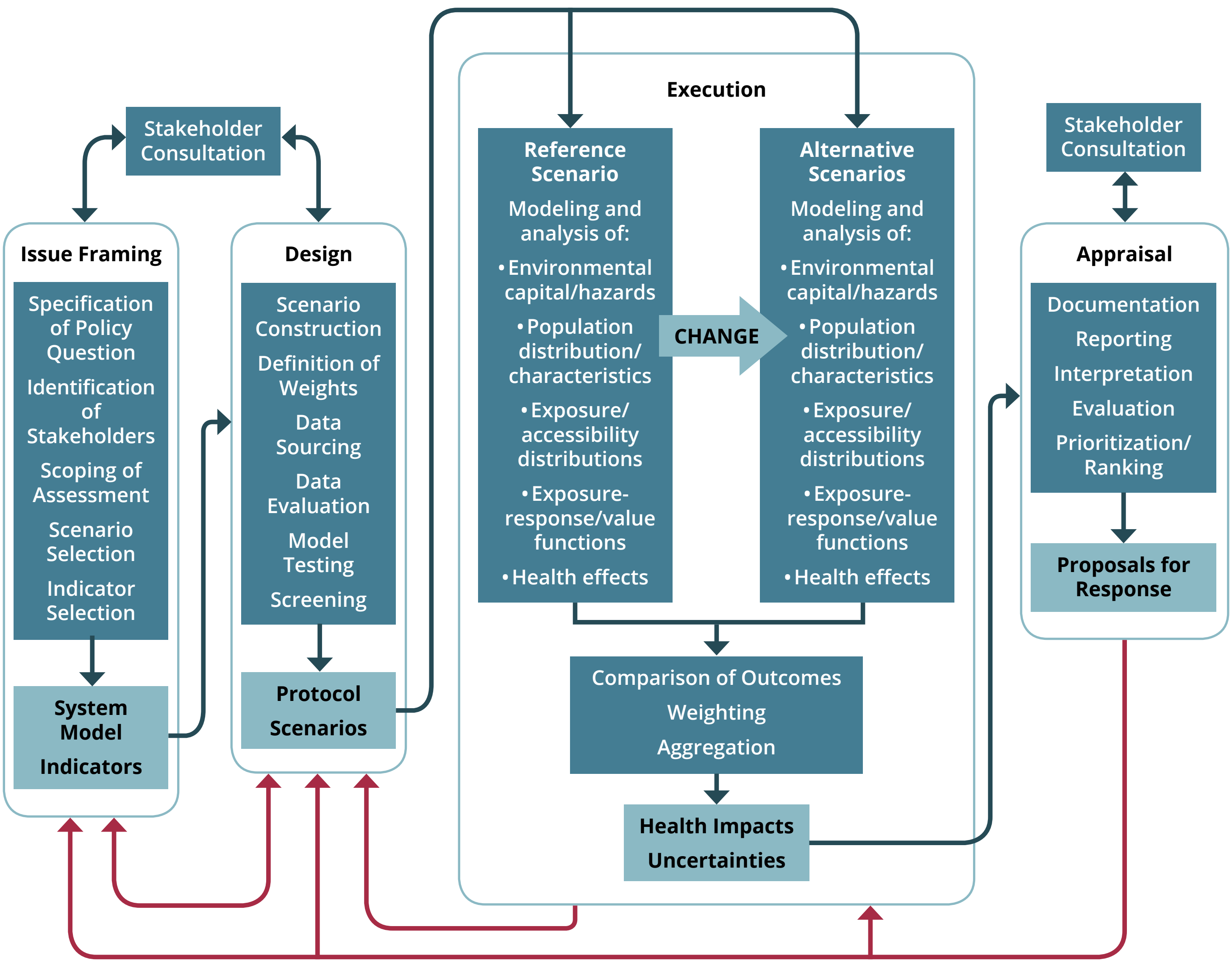


Figure 1. An operational framework for an integrated environmental health impact assessment. *From Briggs (2008).*

managers, environmental non-governmental organizations, municipal elected and staff officials, public service, water and wastewater managers, local planners, state emergency management and public health planners, and health care leaders and associations were enlisted in developing the background information for the project and in identifying the resources needed to assess the vulnerability of water and wastewater infrastructure and the access to health facilities. Then the communities pilot-tested and evaluated the tools. With further refining, the result is this guidebook. The intention is to guide communities that wish to assess their susceptibility to flooding impacts. An outcome of the tool is a list of flood resilience best management practices not currently used by the community. The guide will assist communities in conducting their own assessments, finding partners to conduct the assessments, or contracting out an assessment as best meets their resources and capacity to conduct the technical and engagement work needed.

An overview of the project with detailed information about the Geographic Information System (GIS) resources and analysis used has been published as Linking Water Infrastructure, Public Health and Sea Level Rise: Integrated Assessment of Flood Resilience in Coastal Cities in Public Works Management and Policy (2018), authored by Tom Allen and the rest of the project team.

Questions about the methods and resources can be directed to the authors. Links to spreadsheet resources and videos needed to conduct this assessment as described can be found on the S.C. Sea Grant project webpage.

Purpose of the Guidebook

Who should use this guide and why?

The purpose of this guidebook is to provide coastal communities with a resource to investigate vulnerable infrastructure that poses a risk to public health in our changing climate, with an emphasis on flooding. This guidebook provides stepwise instructions (Figure 2) on how to use our novel mixed-methods Susceptibility Index (SI) to conduct infrastructure and public/environmental health risk assessments. Our intention is for the SI to be transferable to various weather and climate scenarios and used as a preparation toolkit for public health officials, emergency managers, hospital preparedness coordinators, and local municipalities.

The 5-Step Assessment Process

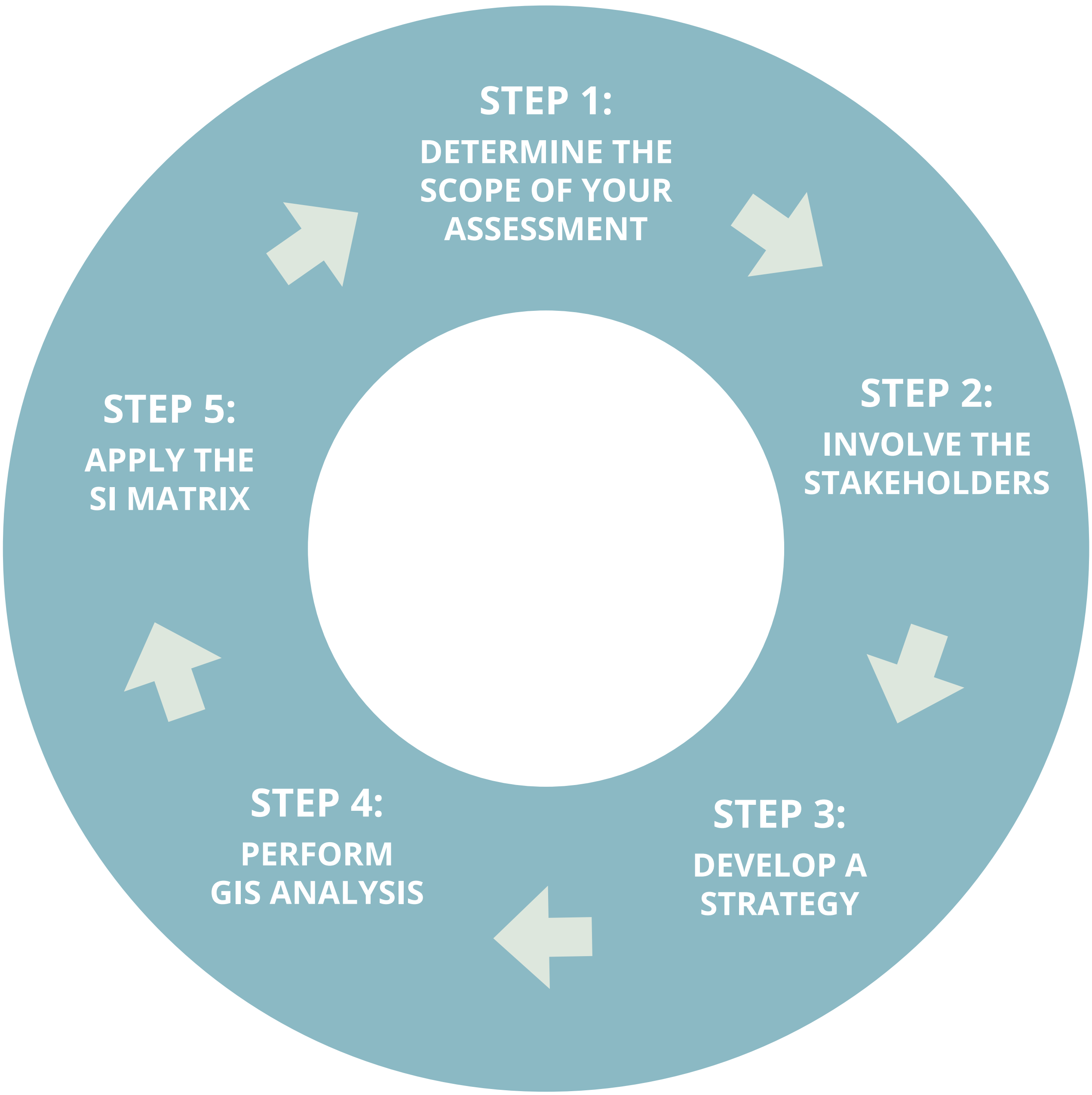


Figure 2. *Multisector cyclic approach for conducting a community level assessment.*

Key Terms

The definitions used to develop the manual

1. Susceptibility: the degree to which a system is open, liable, or sensitive to climate stimuli (International Panel on Climate Change [IPCC], 2014, p. 650)

2. Vulnerability: the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes; a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (Melillo, Richmond & Yohe, 2014, p. 672)

3. Resiliency: a capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimal damage to social well-being, the economy, and the environment (Melillo et al., 2014, p. 672)

4. Sustainability: the ability to be maintained at a given rate or level

5. Municipal Government Sector: government buildings, police/fire department buildings, and emergency routes

6. Water Infrastructure Sector: pipes, pump stations (lift stations and elevations), and water and sewage treatment plants, routes to and from facilities

7. Hospitals / Healthcare Sector: critical infrastructure, secondary support facilities (urgent care centers, pharmacies), dialysis centers, and transportation to and from health facilities

8. General Population: socio-economic status, race/ethnicity, population density, Medicaid/Medicare beneficiaries, and emergency shelter locations

9. Preparation: protocols, investments, studies, and plans aimed at reducing the impact of an event before it occurs

10. Absorption: operations, contingency decisions, real-time assessments, and "eleventh-hour" actions aimed at maintaining critical functions during the duration of an event

11. Recovery: processes, enterprises, projects, and undertakings aimed at restoring infrastructure/organizational function after an event

12. Adaptation: changes, improvements, reassessments, and adjustments that make a system less susceptible to impacts from a given event

13. Scenario: sets of assumptions used to help understand potential future conditions, such as population growth, land use, and sea level rise. Scenarios are neither predictions nor forecasts. Scenarios are commonly used for planning purposes (Melillo et al., 2014, p. 672)

Issue Framing

The Risk to Public Infrastructure

Infrastructure systems are critical cornerstones of human civilization. Damage to infrastructure from natural disasters can result in catastrophic economic losses, unnecessary societal suffering, and a variety of public health consequences (Oyer, 2014; Wilbanks & Fernandez, 2014; Heaney et al., 2013). The American Society of Civil Engineers (ASCE) gave American infrastructure an overall grade of D+ in 2013, with wastewater, levee, and drinking water infrastructures lowering that average with respective grades of D (Herrmann, 2013). This finding was repeated in the 2017 infrastructure report (ASCE, 2017); most of the country's water and wastewater piping is approaching the end of its lifespan, according to the American Water Works Association (Qureshi & Shah, 2014). A year after the ASCE's infrastructure assessment, researchers at the Oak Ridge National Laboratory prepared a report for the Department of Energy, which found "a number of vulnerabilities and impacts on American infrastructure as a result of climate change" (Willbanks & Fernandez, 2014). Extreme weather events such as hurricanes, earthquakes, flash floods, and powerful storms will increase disruptions of infrastructure services in many locations. In addition, longer-term climatic shifts such as sea level rise and associated tidal flooding will also endanger the functioning of current infrastructure systems (Tate & Frazier, 2013).

This vulnerable infrastructure is at greater risk in areas "repeatedly exposed to extreme weather events, located near bodies of water, and already stressed by demand levels exceeding what they were designed for" (Willbanks & Fernandez, 2014), meaning that coastal urban environments are the most vulnerable communities in terms of incurring infrastructure damage from climate change. Coastal counties are the fastest growing urban population centers in the country making coastal urban environments especially vulnerable to disruptions in water infrastructure.

Infrastructure and Public Health

Over the past 50 years, the frequency and intensity of natural disasters have increased markedly in the United States (World Health Organization, 2003). Experts predict that as time progresses, regions already experiencing severe weather events from heavy rains, droughts, or changes in weather patterns in the U.S. will experience more frequent and intense climate-related changes, exacerbating existing health concerns and creating significant new public health challenges (GlobalChange.gov, n.d.).

As the planet continues to warm, experts predict significant changes in the natural environment will intensify and increase existing risks while creating new public health concerns for human systems (IPCC, 2014). While the influences of weather and climate on human health are complex, significant health outcomes, either observed or projected, include impacts

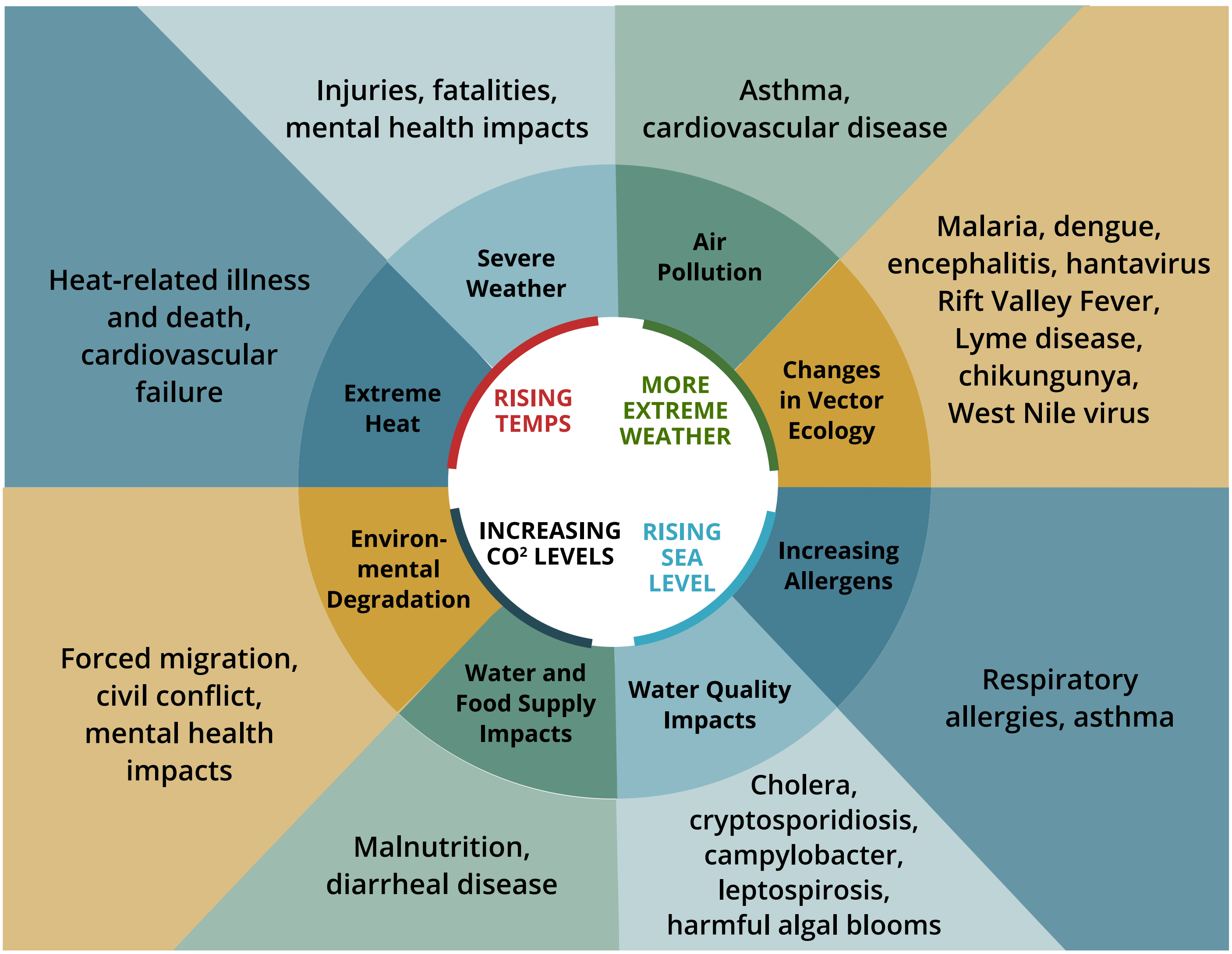


Figure 3. Impact of Climate Change on Human Health *(National Center for Environmental Health, 2016)*

from heat-related morbidity and mortality from extreme high temperatures (Basu & Samet, 2002; Curriero et al., 2002); respiratory diseases from poor air quality (Viegi, et al., 2006), aeroallergens (D'Amato & Cecchi, 2008), and wildfires (Finlay et al., 2012); seasonal distribution of vectors leading to increased vector-borne and infectious diseases from flooding and introduction of new pests and pathogens into new regions (Mills, Gage & Khan, 2010); food security (McMichael, Woodruff & Hales 2006); water quality (Karl et al., 2009); injuries and illness (Kiefer et al., 2016); mental health and stress disorders (Padhy et al., 2015), and nutrition impacts of lessened crop yields (IPCC, 2014).

The primary reasons we should value water and water infrastructure investments more than we do currently have to do with water's effect on public health. Clean drinking water as well as the proper removal and treatment of wastewater are associated with positive health outcomes time and time again. Proper pipe maintenance and treatment protocols protect the public from health threats such as chemical contamination, ingestion of heavy metals, and a number of potentially life-threatening viral and microbial infections.

Reinvestment in water infrastructure has not been a top national priority, and as a result the condition of our public infrastructure lags behind in an increasingly competitive global economy (Ajami, Thompson & Victor, 2014). From 2010 to 2020, the annual gap in required water infrastructure investment grew from $54.8 billion to $84.4 billion (ASCE 2017). While this represents a huge overall investment, the gap analysis by the U.S. Environmental Protection Agency (EPA) found that consistent small increases in rates would be generally sufficient to pay for increasing operating and maintenance needs.

> "Investing won't just safeguard our health – it also will help America's bottom line, as one-fifth of the U.S. economy depends on clean water. Every $1 we spend on water infrastructure improvements generates $6 in returns."
>
> *– Riley Ohlson (Alliance for American Manufacturing)*

Learning from Past Disasters

There are many lessons from Hurricane Katrina and other large-scale events that can be used by emergency management, planners, researchers, and other coastal managers. One of the most important lessons to take from these historic storms is the benefit of using clear and tailored communications about personal preparedness, disease and injury prevention, and available support services.

Culturally sensitive communication messaging before, during, and after a major event is critical. During Hurricane Katrina, low-income African Americans perceived transportation, sheltering, and other inequalities as major barriers in the midst of the disaster (Elder et al., 2007). Many felt that providing transportation and sheltering services would not be enough to spur them to evacuate (Elder et al., 2007). This provides further evidence that low-income and minority populations may not understand or value current communication messages and strategies. To reach these populations, multiple studies have recommended engagement via community, religious, and social groups could prove more effective than traditional methods (Eisenman et al., 2007).

An influential, but often overlooked, stakeholder during a disaster is the media. In the aftermath of Hurricane Katrina, for example, most of the stories covered issues with the government's response (Barnes et al., 2008). However, the level of community and individual preparedness was not held to the same standard, or even discussed (Barnes et al., 2008). After Hurricane Florence in 2018, North Carolina saw multiple prolonged power outages and massive flooding throughout the eastern part of the state. Many county schools were not back in session for six weeks. Problems included carbon monoxide poisoning from using a generator indoors or too close to the house, lack of access to prescription medication refills and dialysis treatment, spike in heat-related illness, and floodwater contamination of structures resulting in mold issues (Christensen, 2018). However, most media articles discussed response and mitigation rather than critically evaluating preparedness and responsibility at the individual and community level (Barnes et al., 2008). Many state agencies are working hard to encourage personal preparedness, especially of vulnerable populations. However, more discussion and transparency from the media would go a long way in holding individuals and communities responsible for their role in preparedness.

Overall, the method presented in this guidebook presents a unique opportunity for professionals in the health sector (hospitals and secondary/tertiary-care facilities, dialysis centers, etc.), the utilities sector (water, sewer, electric, etc.), and the municipal government sector to come together and discuss public health impacts of a future extreme-weather event. The goal is to improve communications among the sectors linked with public health, using research-informed, data-driven, and multidisciplinary approaches, in order to improve our community-level preparedness in coastal communities.

Approach

A stepwise susceptibility assessment system, the Susceptibility Index (SI) was developed and tested in Charleston, S.C. and Morehead City, N.C. The steps discussed here include specific examples from both cities for context and comparison. Although the guide was developed using a specific weather-based flooding scenario incorporating a specific climate projection, the GIS-based SI can be used with different storm scenarios and even modified to analyze other issues, both from short- and long-term perspectives. The SI tool was developed to measure vulnerability and resilience, and therefore susceptibility, from four perspectives or sectors; municipal government/emergency response, water system/utility network, hospital system, and local population. Completion of the exercise will provide each sector with best management practices to improve their SI.

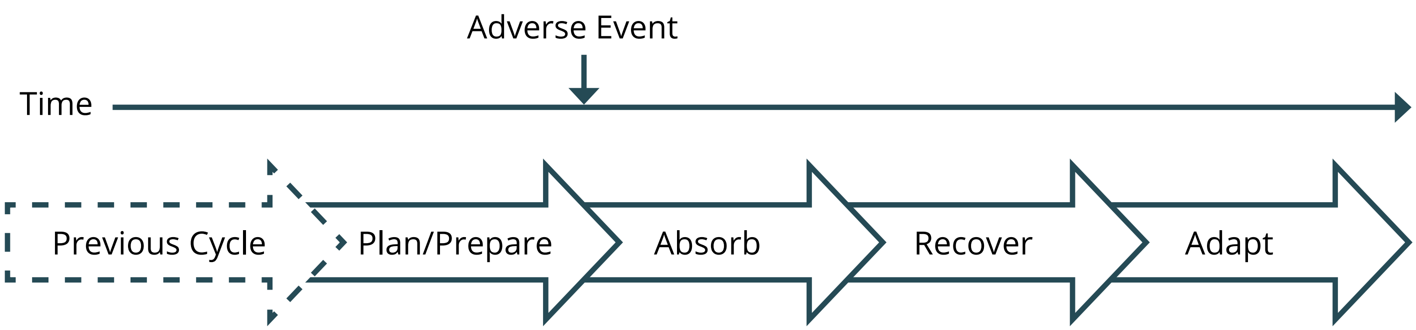
Consider this susceptibility assessment approach as a cyclic process (Figure 2) which continuously refers back to the desired public/environmental health endpoints. It is important to adapt this process to best fit each community. Using continuous feedback, the steps are 1) determine the scope of your susceptibility assessment, 2) involve the stakeholders, 3) develop a strategy, 4) conduct GIS analysis, and 5) apply the SI index (Figure 2).

STEP 1 Determine the Scope of Your Susceptibility Assessment

a. What are the benefits of an environmental and public health assessment?

Environmental health and public health risk assessments serve a dual purpose: to measure the impact of the threat and to estimate the potential benefit of a policy or program. The impact is measured through a risk assessment to predict potential risks to human health or the environment. The benefit conscribes a health impact assessment or environmental impact assessment. The SI will provide an effective measure of the potential influence of specific public health threats, while the tabletop exercise will provide a platform for interdisciplinary conversation and development of programs and policies to mitigate the threats of climate change on coastal communities.

These assessments can be adapted to fit your community's specific goals. The Army Corps of Engineers 4x4 Matrix (Fox-Lent, Bates & Linkov, 2015; Figure 4) framework was employed for the SI, since it uses a mixed-methods approach and can be scaled for organizations of varying size. The rows of the matrix address the physical, informational, cognitive, and social components of a complex system; i.e. a town, city, county or state. Meanwhile, the columns of the matrix address the four main stages of the disaster cycle: preparedness, absorption, recovery, and adaptation. The intersection of each row and column provides specific



	Plan/Prepare	Absorb	Recover	Adapt
Physical	State and capability of equipment and personnel, network structure	Event recognition and system performance to maintain function	System changes to recover previous functionality	Changes to improve system resilience
Information	Data preparation, presentation, analysis, and storage	Real-time assessment of funtionality, anticipation of cascading losses and event closure	Data use to track recovery process and anticipate recovery scenarios	Creation and improvement of data storage and use protocols
Cognitive	System design and operation decisions, anticipation of events	Contingency protocols and proactive event management	Recovery decision-makers and communication	Design of new system configurations, objectives, and decision criteria
Social	Social networks, social capital, institutional and cultural norms, and training	Resourceful and accessible personnel and social instutitions for event response	Teamwork and knowledge sharing to enhance recovery	Addition of or changes to institutions, policies, training programs, culture

Figure 4. The Resilience Matrix Framework *(Fox-Lent et al., 2015).*

discussion questions for evaluating community resiliency within sectors of interest.

This approach allows communities and organizations to assess their capacity to deal with emergency events through the different stages of disaster. When the SI combines scores from the complex system rows, the rankings can help your community understand the relative gaps in your hazard plans according to the disaster phase and system component.

b. What are the environmental risks in your community?

To better understand the environmental risks likely occurring in your community, you should start by identifying potentially hazardous environmental conditions occurring locally or regionally that could affect water infrastructure, then apply one or more climate change impacts. For the SI, total flooding is used; no matter whether storm surge or rain or sea level rise, as these present cumulative impacts. Examples of conditions often associated with negative outcomes on water infrastructures include:

- Aged pipes/undesirable pipe material
- Poor infrastructure funding mechanisms
- Hurricanes and strong storms
- Changes in local hydrology/geology

The community's hazard mitigation plan is a useful source of in-depth information about potentially hazardous conditions that can pose threats to human life and health. These are plans approved by the Federal Emergency Management Agency (FEMA), and are aimed at reducing the loss of life and property, both immediately after disaster and in the long term. Not every municipality will have a hazard mitigation plan, and if yours does not, this assessment

Make the issue CLEAR!

- **What is the problem?**
- **When and where is it likely to take place?**
- **Has the issue been discussed previously?**
- **Are there written procedures or policies relating to this matter?**
- **What organizations are responsible or share responsibility for preventing or mitigating the issue and hand?**

may provide information for your community to use in developing one.

Many environmental factors can place burdens on individual health, and it can be confusing to know where to begin. Engage the community throughout the process to make your health assessment more meaningful and to ensure that community priorities are included. Public health assessments have much better support when residents are involved and thus committed to the process of identifying health issues and developing strategies for addressing those issues. To help discover environmental conditions that threaten public health, consider:

- Polling local residents to learn what they perceive as health hazards
- Hosting focus groups, where public health experts guide discussion on the relationships between human health and the environment
- Holding public comment sessions to discuss your plan for a community health assessment, and using the comments and inputs received to improve it
- Creating public forums or other means to facilitate open discussion to learn about innovative solutions to local problems

c. Define the area of your environmental and public health assessment

After identifying the list of conditions or factors that could impact water infrastructure, it is time to set priorities for the SI and define the geographic area to be included in the assessment. Consider using predefined boundaries such as the service area of your local water

Determine the appropriate scope of your assessment using SMART – Specific, Measurable, Achievable, Realistic, Time-phased

- **Make your assessment scope practical; do you have accessible data for your selected region?**
- **Does this area have municipal or community level partnerships with health networks or utility providers?**
- **Are there threats to water infrastructure or public health shared by neighboring communities?**

utility provider, municipal boundaries or areas/regions most prone to natural/technological disasters to define the focus area.

Then determine which hazards the assessment will address. To understand which hazards are most salient to your study, start by challenging yourself to identify how climate change

Climate-Related Hazard	Water Infrastructure Issues	Local Issues	Potential Health Impacts	Resources & Mitigatory Processes
Increase in annual precipitation	Overwhelming storm drainage capacity	Frequent flooding and transportation issues from road closures	Drowning, dermatitis, injuries, accidents, evacuation complications, secondary health conditions	None currently
Increase in seasonal temperatures	Potable water contamination	Algal blooms in local water bodies	Exposure to cyanotoxins in water bodies, drinking water, or via consumption of seafood	Water utility adding additional filtration mechanism
Sea level rise causing hydraulic shifts in local groundwater salinity	None yet (Future concerns: corrosion, changing intake source, etc.)	Saltwater intrusion up river or into aquifer(s)	(Future concerns: loss or contamination of potable drinking water)	Local municipalities and water utility agents planning construction of new dam/ reservoir
Increasing storm intensity	Access to service facilities (i.e. generator failure at pump stations)	Road closures due to inundation	Power, water, or food shortages, injuries, acute gastroenteritis, mosquito-borne disease	Municipalities working with transportation departments to identify at risk routes
Land subsidence, coastal erosion, sea level rise	Elevation of generators at pump stations	Rising tidal influences (ex: King Tides)	Exposure to Vibrios, Staph, HABs, mold/ endotoxins	None currently

Table 1: *Example table of climate hazards, infrastructure damage, and public health impact from Charleston, S.C., 2018.*

impacts will affect public health or water utility services. Lastly, check with your assessment team or local stakeholders to see if any protocols are being implemented to prepare for negative health/infrastructure outcomes associated with climate change. Keeping all of this information in a chart might make it easier to determine what hazards are most important to your community (Table 1).

d. Sketch a timeline of public health impacts

An overwhelming number of public health impacts might need to be considered following a water infrastructure failure in a coastal community. To organize the impacts considered for the pilot study, a timeline of potential public health events following a disaster scenario was created using Lane's Water Infrastructure–Public Health Impacts Logic Model (Figure 5). For our pilot, we developed a demonstration disaster. A future hurricane event that is

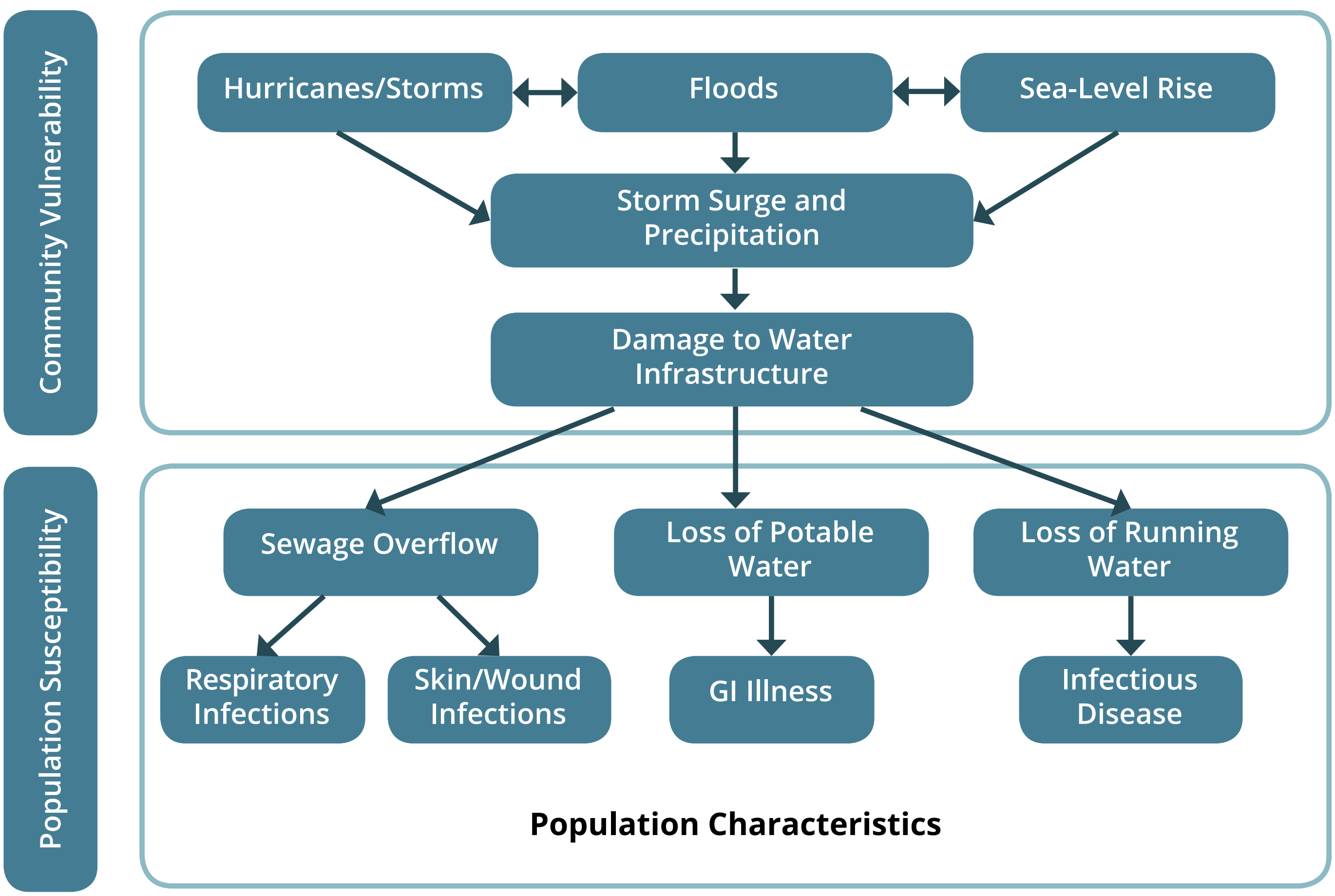


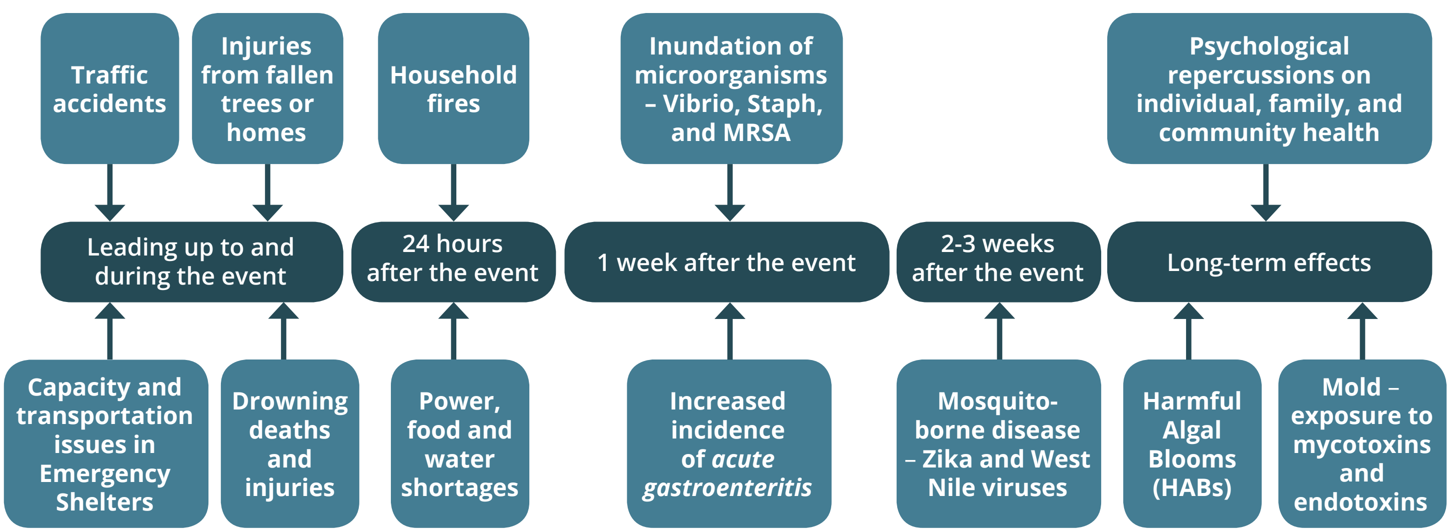
Figure 5. *Water Infrastrucuture – Public Health Impacts Logic Model (after Lane el al, 2013).*

compounded by sea level rise projections and heavy antecedent rains (discussed in detail later) was used. The literature of recent and related public health disasters – including hurricanes Katrina, Matthew, and Sandy, and the Flint, Michigan water-supply issue – as well as interviews with local experts in Charleston were reviewed and supported the choices for the potential effects displayed on the timeline below. In the event of a disaster on the coast, the public's health will be compromised and should remain the top priority at every stage – preparedness, absorption, recovery, and adaptation (See Figure 4).

e. Timeline example – Charleston, South Carolina

The discussion below uses Charleston as an example, but the impacts will likely be similar in most locations. However, depending on local conditions relating to land use, population density, and characteristics of the event, the specific time frames may vary.

Leading up to and during the event. If an official (varies by state and county) ordered evacuation of the coast, many people should have complied and left the area. However, road closures, heavy traffic, and increased stress may lead to an increased number of traffic



** Special attention should be placed on inequalities and vulnerable persons during every phase – preparation, response, recovery, and adaptation, as these imbalances can lead to disproportionate health effects,

Figure 6. *Timeline of Potential Public Health Impacts Following Water Infrastructure Failures in Charleston, South Carolina (Allen et al 2018).*

accidents. Some persons may choose not to evacuate, find that they cannot evacuate, or even get trapped in their homes during an event. According to the Medical Examiners Weekly Report during Hurricane Hugo, drowning caused six deaths and impact from fallen trees or homes caused seven deaths (CDC, 1989).

Identifying and evacuating vulnerable populations proved to be especially difficult during Hurricane Matthew and would likely prove to be the most difficult public safety impediment prior to this event. South Carolina Department of Health and Environmental Control (SCDHEC), the state organization responsible for public health and emergencies, defines vulnerable populations as geographically, economically, or culturally isolated persons, persons with low English fluency, physically or mentally impaired persons, and/or children. At that time these persons were not properly accommodated with the emergency shelter structure in South Carolina. SCDHEC runs a limited number of Special Medical Needs Shelters (SMNS). However, eligibility criteria for the shelters are stringent – only persons who require electricity to survive AND have a caregiver present can be admitted to a SMNS. For example, during Hurricane Matthew (and 2 days prior), 124 persons called into the SMNS triage center for help; only 13 persons were eligible for a SMNS. (Christensen, 2018) The common themes identified from these phone calls were: needing assistance to evacuate, needing a caregiver to be admitted, and caregivers who called with multiple patients in need. Persons who are not eligible for SMNS are referred to an American Red Cross general population shelter. These shelters may be overburdened and are frequently under-prepared to serve the needs of these vulnerable persons. (Christensen, 2018)

24-hours after the event. Emergency sheltering will likely still be active at this time. Most shelters are prepared to operate for a maximum of three days. Therefore, depending on the status of power and water availability, as well as the number of individuals being served at these shelters, there could be power, food, and water-supply shortages.

In a prolonged flooding event, the inundated area may result in road closures due to fallen trees, downed power lines, or other debris. If evacuated, the majority of the population would be advised not to return to their homes at this time. However, persons who did not or could not evacuate can be trapped in their homes and susceptible to injury or illness (CDC, 1989). According to the Medical Examiners Report, after Hurricane Hugo household fires caused by candle use resulted in nine deaths, the majority of which were young children (CDC, 1989). This may be a concern immediately following an event if there are sustained power outages. Road closures and transportation issues can prevent these vulnerable populations from receiving medical care, durable medical equipment, or prescriptions they may need to manage pre-existing conditions. Particularly of concern are end-stage renal disease patients who receive in-home or in-facility dialysis treatments. Access to this life-sustaining treatment was an issue during Hurricane Matthew in 2016 and the October 2015 flood in South Carolina. Additionally, prolonged power outages might result in an increase in carbon monoxide poisonings and carbon monoxide-related deaths caused by people using gas-powered generators inside or close to their homes.

One week after the event. SCDHEC should be working with local hospitals and pharmacies to actively survey for an increased incidence of acute gastroenteritis, including vomiting, diarrhea, and non-infectious rash. This could be caused by contamination of potable drinking water supply due to a water line break. If flooding has impacted the area, these symptoms could be caused by physical contact with, or inhalation of, flood waters which can contain a mixture of hazardous substances (Svendsen, 2017). Interaction with floodwaters or loss of potable drinking water are generally the causes of an uptick in acute gastroenteritis during disasters.

If emergency sheltering is still in effect, shelters should be monitored for disease using pre-existing epidemiology surveillance tools specific to the site. The longer these temporary refuges remain operational, the greater the probability of an infectious-disease outbreak. An example of a similar outbreak occurred in evacuees who took refuge at a common site in Houston, Texas following Hurricane Katrina (CDC, 2005). Although there were no deaths, 1,165 persons exhibited gastrointestinal symptoms, including diarrhea and/or vomiting. The outbreak, later identified as norovirus gastroenteritis, occurred nearly two weeks after the event (Yee et al., 2007). *Vibrios*, *Staphylococcus aureus*, and Methicillin-Resistant *Staphylococcus aureus* (MRSA) infections should also be actively monitored due to the large inundation of microorganisms (both brackish and saltwater-based) that could contaminate the area (Levin-Edens, Meschke & Roberts, 2011). Local physicians should be alerted by SCDHEC to watch out for infections caused by contaminated water contact with open wounds (Levin-Edens et al., 2011) or consumption of contaminated shellfish. Hospital staff should be encouraged to immediately report these infections to the health department (CDC, 2005; Yee et al., 2007). Vibrio infections caused five deaths during Hurricane Katrina (McMichael, 2015; Yee et al., 2007).

Two to three weeks after the event. The severity of the flooding and the resulting amount of standing water in the area, the state of the roads, and temperature will contribute to the threat of mosquito-borne disease in the area. Under normal operations, SCDHEC and county mosquito control work closely to regulate and monitor the local mosquito population

However, if routine ground control cannot be carried out, adult mosquito populations could spike, resulting in an increased probability of infections in the local populations (Harnes and Hayes, 2017). Air support would need to be initiated as soon as possible to kill the adult-stage mosquitoes, especially on dredged sites (Harnes and Hayes, 2017).

West Nile and Zika viruses are of particularly concern in the Charleston area because they are both transmitted via the bites of infected “container-breeding” mosquitoes from the genus *Aedes* (Harnes and Hayes, 2017). West Nile and Zika viruses present challenges from a clinical standpoint because only one in five people exhibit symptoms (Ball, 2017). Some Zika symptoms include, but are not limited to, fever, rash, and red eyes (Ball, 2017). Similar to Zika, symptoms of West Nile virus include fever, body aches, vomiting, diarrhea, skin rash, and headache (Ball, 2017). If left untreated the virus can lead to disorientation, convulsions, and/or paralysis (Ball, 2017). However, Zika may prove to be a greater public health threat because it can be sexually transmitted and can lead to long-term malformations to unborn children in utero, resulting in a condition called microcephaly (Ball, 2017). Therefore, it is important for local hospitals, SCDHEC, urgent-care clinics, and emergency shelters to create active surveillance systems, while working closely with county mosquito control, to preventatively monitor the exposed persons and curtail the population-level impacts of these emerging infectious diseases.

Long-term effects of the event. Harmful algal blooms (HABs) can have both public health and ecological impacts in Charleston (Svendsen, 2017). Due to Charleston’s increasing population and therefore related nutrient contributions to surface water, HABs are concerning following normal rain events (Lewitus & Holland, 2003). Increased nutrients – specifically nitrogen and phosphorus – and erosion can spike phytoplankton growth, causing nutrient plumes and corresponding dead zones that can affect the local marine wildlife (Reed et al., 2016). HABs are an issue to human health because exposure via drinking water, seafood consumption, or physical contact with these toxic cyanobacteria or dinoflagellates can effect the nervous system in extreme cases (Svendsen, 2017).

Psychological repercussions for those affected by the event can have long-term impacts on individual’s, as well as, the recovering community’s health (Schmeltz et al., 2013; Zahran et al., 2008). Historically, minority and lower-income populations have been more susceptible to the long-term impacts of extreme events (Rufat et al., 2015). Residents of lower socioeconomic status who live in lower elevation areas of the city that are more prone to flooding are at risk for increased mortality, and these communities tend to take much longer to physically and mentally recover after an event (Jonkman et al., 2009). Due to financial strain and imbalanced severity of damages, it takes longer for these communities to physically rebuild (Zahran et al., 2008). A delay in a return to normalcy and a greater loss of resources can lead to psychological distress (Harville et al., 2015; Zahran et al., 2008). Nevertheless, early identification of these inequalities provides opportunities for intervention and additional support for these communities using a bottom-up approach to community preparedness and response (Schmeltz et al., 2013).

f. Explore ways to mitigate environmental and public health impacts

Once the range of impacts and the timeline have been determined, focus will turn to preparation and absorption. Public health preparedness is a process that occurs many months, and even years, before an event. It involves community education and engagement in the form of workshops, targeted communication messaging, and the building of interpersonal relationships through collaborations and working groups.

The period leading up to, during, and 24 hours after the event is considered the absorption phase. The ability of a community to absorb the effects of an event is directly correlated to the functionality and amount of infrastructure, personnel, and overall capacity of the municipal government, health sector, and water sector.

In order to lessen the impacts weeks after the event, the recovery process should be carefully evaluated. The sectors involved should have effective contingency plans following emergency operations in order to return the community back to normal operations. Depending on the severity of the event, the recovery process can take months or even years. It is imperative for community support to continue during this critical period.

Lessons from the first three phases – prepare, absorb, and recovery – should be used to adapt in the long term. Multiple professions should be involved in order to create sustainable solutions that support coastal resiliency and protection.

STEP 2 Involve the Stakeholders

a. Determine relevant stakeholders and decision-makers

At this stage in the process, you should have:

- One or more clearly communicated issue(s) of concern
- A defined area over which the assessment will take place
- A basic understanding of the relationship between the local issue and climate change
- A list of potential impacts these issues could cause to public health or water infrastructure, as they occur over time, and thus an expanded knowledge of the sectors that should be consulted in refining the scope of the assessment

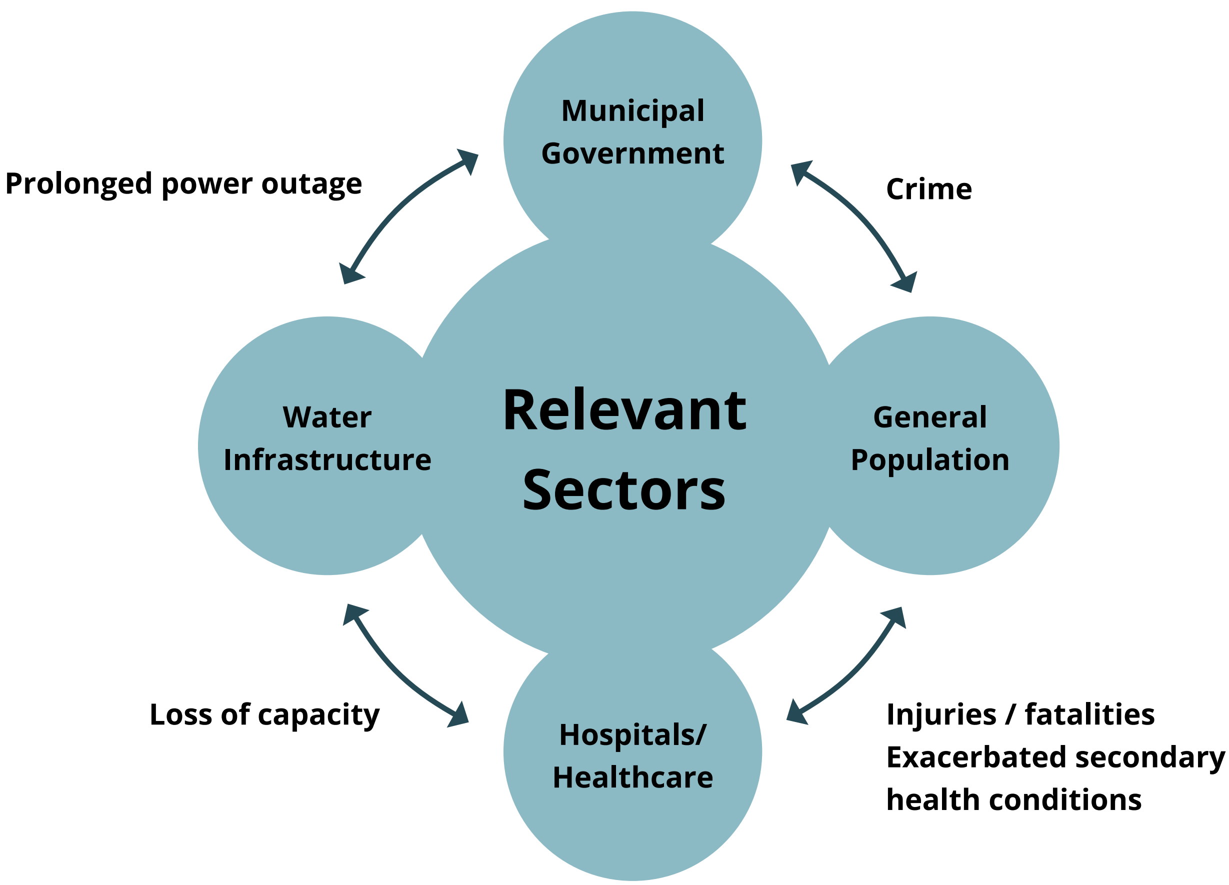


Figure 7. *Intersection of the four sectors used in the pilot study – Water/Wastewater Infrastructure, Hospitals/Healthcare, General Population and Municipal Government. Arrows between sectors denote deleterious outcomes that could emerge if the connections between those silos diminished.*

b. Develop interview/focus group questions

To gain perspective on future tasks and current issues, consider using stakeholder engagement through small focus groups or in-person interviews. These personal communication methods should be aimed at bringing together knowledge and information held by specialists in public health, emergency management, coastal hazards, and water/wastewater infrastructure. Our project team developed interview questions specifically designed to gain stakeholder perspective on:

- The current condition of local water infrastructure
- The potential for that water infrastructure to function under extreme weather events
- The capacity of the local health care system to cope with rapid increases in patients or with utility failures
- Existing municipal plans for water-based disaster scenarios

c. Analysis to understanding the interviews as a whole

Interviews and focus groups will likely provide your assessment with a rich source of information pertaining to local threats. However, sorting through this information can quickly become cumbersome depending on factors such as:

- The number of participants interviewed
- How many questions each participant is asked
- The level of detail participants provided during their response

Consider developing partnerships with local colleges and universities to conduct this work. In small communities, notes from the interviews may provide enough information.

Ask questions to your team such as:

- **What climate hazards do you expect?**
- **What systems are most vulnerable? For example: hospitals, transportation, wastewater, communications, etc.?**
- **What are your objectives and public health endpoints?**

STEP 3 Develop a Strategy

After collecting and understanding the information on hazards and potential impacts to the community and engaging stakeholders, the next step is to develop a strategy with your team to prepare for and hold your tabletop assessment. This step is critical, and should be revisited at multiple points moving forward, because it ensures that every team member is on the same page and that time and resources are used effectively.

a. Prioritize health and climate hazards

Addressing all potential heath or climate hazards faced by a local community in a single exercise might not be feasible or possible. For this reason, your team should carefully consider the concerns of local stakeholders and prioritize expected health and climate hazards by infrastructure vulnerabilities, probability of occurrence, magnitude of effects, and financial consequences. Climate and health scenarios that are readily addressed by current infrastructure, or exacerbated by poor infrastructure, should be appropriately assessed for their inclusion or exclusion during the exercise. Each group of stakeholders will likely have an idea of which infrastructures are of concern, and which are relatively reliable. However, it is up to you to facilitate and ensure that the exchange of information occurs. Knowledge of infrastructure vulnerability may be too general or incomplete. It is important to work with stakeholders in obtaining or creating quantitative data sets which can measure vulnerability in a more objective fashion (for example GIS maps, historical failure rates, operational capacities/limits, etc.)

b. Choose the right approach

Thousands of approaches are used across the globe to manage complex decisions involving public health, climate change, and infrastructure. One thing to keep in mind during your search for an appropriate framework is to realize that many of these approaches borrow heavily from one another, and almost all of them have common or comparable processes. When you are choosing a framework to assess your resilience, make sure the objectives of your exercise are shaped not only by the local vulnerabilities, but also by the depth of information stakeholders are interested in, the research or technical capabilities of your project team, and the degree to which the approach can change to incorporate new information. In planning the pilot project, a number of resilience and vulnerability assessments were considered before deciding to use the Army Corps of Engineers' Coastal Resilience Assessment. This framework was selected because its methodological requirements fit within the abilities of our research team. It is highly modular, can be scaled up or down to include more or less information, and is straightforward enough to allow it to be quickly understood by individuals from a variety of backgrounds and levels of experience.

c. Check for essential features

While there are innumerable ways of creating a resilience framework, most frameworks will operate on the following basis (Figure 8):

- The identification of hazards/potential impacts
- Assessment of system/infrastructure vulnerability to those impacts
- Development of recommended courses of action to prevent, respond, or recover from impacts
- Records of adaptive implementations and how they affect impacts and susceptibility

Make sure the framework you adopt or create features these four aspects.

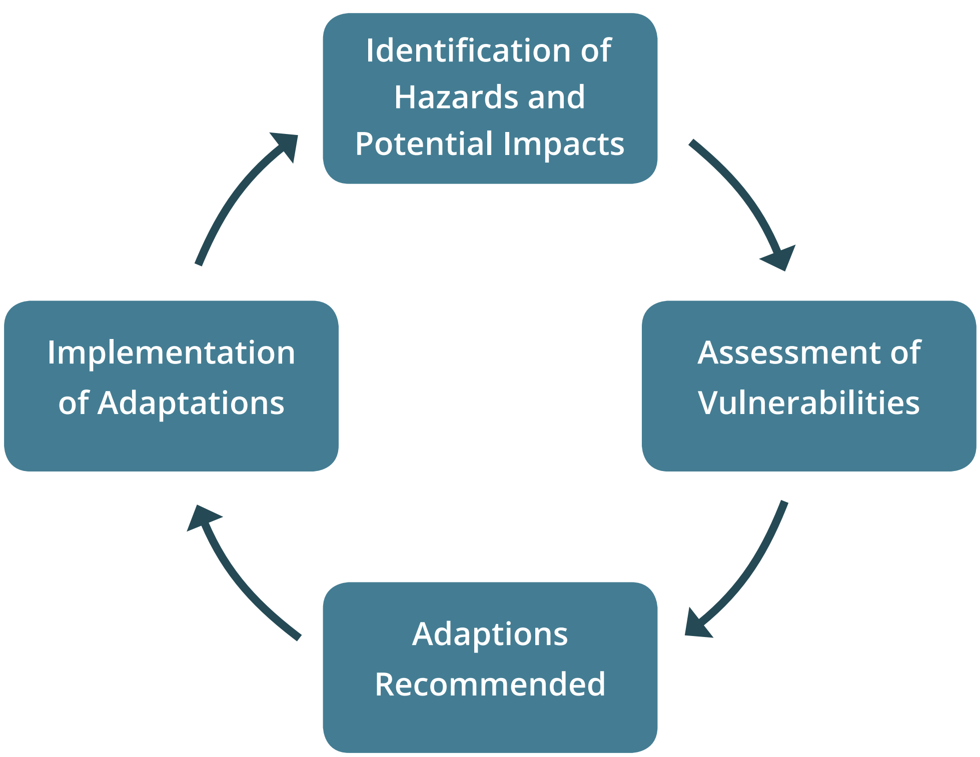


Figure 8. *Fundamental components of any resilience assessment.*

STEP 4 Performing GIS Analysis

To understand the relationships of your physical landscape, water and waste water assets, transportation, cultural and medical resources during flooding it is important to use a Geographic Information System or GIS.

GIS datasets that cover a wide variety of hazards and potential impacts are necessary for an integrated view to facilitate the decision-making processes that support public health and water infrastructure. These data can be generally characterized within three broad groups, which are detailed with respect to acquisition, analysis, and considerations for sharing in the sections that follow: coastal hazard GIS data and modeling; population demographic and health care facilities and services; and water infrastructure. In general, federal and state agencies are the primary repositories and providers of the coastal hazard data.

a. Where to locate reliable GIS layers

This section identifies a set of robust and well-documented online tools for communities seeking sea level rise and future climate-related coastal hazard layers.

1. NOAA Office for Coastal Management Sea Level Rise Viewer (and GIS data) – Data from the sea level rise (SLR) viewer can be viewed directly online at limited spatial scales. These layers can also be streamed to a desktop GIS as a webmap services (WMS) layer for display (also scale-limited) or alternatively downloaded and used as a direct GIS analysis layer (without scale limitation.) The elevation layers represent a “bathtub” model with a limited degree of hydrologic correction or conditioning, yet the tool can provide useful incremental layers at about one-foot vertical resolution to assess future conditions of static sea level or tidal inundation. The site includes a video instruction, detailed mapping methods, and FAQ.

2. Climate Central Toolkit – Climate Central’s Resilience Toolkit provides online webmaps for visualizing the threat of rising sea levels and storm surges. A variety of tools and interfaces can be used there to assess risk for transportation and population/land use. Tutorial videos and FAQs are also provided.

3. The Nature Conservancy (TNC) Coastal Resilience Tools – The Nature Conservancy provides

a mapping portal for visualizing risk and supporting hazard mitigation and adaptation planning. A network of U.S. and other locations is compiled in coordination with federal agencies and states (Coastal Resilience). While limited to focus areas, these tools typically include a sea level rise simulation and superimposed storm surges. It is possible to integrate these output layers with local data through combining WMS services or acquiring data from TNC directly.

4. United States Geological Survey (USGS) Coastal Change Hazards Portal – The USGS portal focuses on coastal geomorphic changes from hurricanes, other extreme/extratropical storms, shoreline change rates, and sea level rise trends. Broad swaths of the U.S. coastline have been mapped and assessed for coastal vulnerability and forecasted changes. This site provides interactive viewers and downloadable GIS datasets for each of these baseline shoreline and sea level trends. In addition, the site has been augmented to include case studies and extracted data for recent hazard events (e.g., 2017 Hurricanes Harvey and Irma).

These federal and state agencies typically provide wide regional GIS datasets because the extent of the hazards themselves usually is extensive and pervasive. The NOAA National Weather Service (NWS), National Hurricane Center (NHC), and their cooperating state agencies will generally run advanced computer simulations of hydrodynamics with each threatening storm, flood, or other coastal weather hazard. In some states, universities and state agencies may provide additional GIS-based forecasts or risk-mapping products in near real time. For instance, in North Carolina, the University of North Carolina and Renaissance Computing Institute (RENCI) provide updated surge forecasts at fine resolution using the N.C. Coastal Emergency Risk Assessment Tool, although direct linkage of this to desktop or web-based GIS is not provided. For flooding, the N.C. Flood Inundation Mapping Network is another example, again lacking direct local use for GIS integration. Instead, systems such as these must be viewed separately through a web browser. The advantage of such systems is their near real-time currency. However, there is also risk embedded in these modeling systems, wherein they use single-track deterministic forecasting rather than wider, probabilistic methods that can incorporate uncertainty (e.g., storm track, storm wind intensity, precipitation severity, and timing of all of these.) Hence, for operational risk assessment and preparedness between 24 and 48 hours ahead of a disaster, NHC and NWS forecast offices are the undisputed, authoritative sources for coastal hazard data.

For long-term planning and resiliency, academic institutions and specialized state-university-local research efforts can be most useful to advise strategic plans. Such long-term views may incorporate climate change and attendant impacts that are not present in the current operational models. Factors like eustatic sea level rise, local ground subsidence, changes in tidal hydrodynamics, recurrent nuisance flooding, and even rainfall frequency/magnitude may be extrapolated in these products that can span decades into the future. Given uncertainty in future climate changes, a primary consideration and drawback of these research efforts is the need to consider uncertainty in the computer models. This requires careful consideration of risk and sensitivity with respect to the population, buildings, and infrastructure in a given area. Generally, low-lying coastal communities may want to adopt a "no regrets" approach, focusing their consideration of long-range planning in the case of infrastructure on the high scenarios or a wider range of scenarios that include high or even extreme levels of sea level rise.

b. Seeking customized coastal data

1. LiDAR Digital Elevation Data (tutorial here)– Digital elevation data and inundation models are foundational to the analysis of the impacts of sea level rise. Uncertainty in these analyses derives, in large part, from the accuracy of elevation data. Positional error in inundation modeling relates to this uncertainty in vertical measurements and to issues of datum conversion, projection, and interpolation methods. This potential error may cause the inundation zone to fluctuate either landward or seaward. As a consequence, Titus and Cacela (2008) note that estimates of flooded areas under any particular scenario of sea level rise can be expressed as a range of plausible values.

2. Coastal Topographic LiDAR Data Sources – NOAA hosts the Interagency Elevation Data Inventory. Users seeking to replicate this study and develop inundation models should focus on acquiring "bare earth" gridded elevation data (i.e., "Topographic LiDAR.") NOAA's Office for Coastal Management also hosts an overview of LiDAR and a download site with a customizable, user-friendly interface.

3. USGS 3DEP Elevation Program – Seamless gridded elevations are available from the USGS as bare earth DEMs from the National Map.

4. State Repositories – Increasingly, states are taking on extensive LiDAR base-mapping programs to augment existing digital orthophotography collections at the state or local level. For instance, in North Carolina this is the N.C. Floodplain Mapping Program (NC FMP) and in

Virginia, the Virginia Geographic Information Network (VBMP).

5. Tidal Inundation Analysis Tool – Users interested in frequency and duration of flood events can extract statistics from the NOAA Inundation Analysis Tool for numerous tide gauges. The site includes a step-by-step user guide. An example output of frequency of tidal elevations is provided below.

c. Additional useful analysis

Elevation Uncertainty

Multiple studies have affirmed the critical importance of elevation data for the modeling of sea level rise and flooding (Cooper et al., 2013; Gesch, 2009). Gesch (2012) stipulates that input elevation information is a primary contributor to the uncertainty associated with inundation hazard assessments and that, because these data are such a critical component in coastal hazard assessments, the vertical accuracy strongly influences the reliability of the results. Digital elevation data are produced using a variety of methods including: photogrammetry, radar, digitization from analog topographic maps, point surveys, and LiDAR. For the purpose of sea level rise assessments, Gesch (2009) found that LiDAR-derived elevation data are substantially better than non-LiDAR elevation datasets. Utilization of best available LiDAR having both high spatial resolution and accuracy is preferable. A key descriptive metric of the

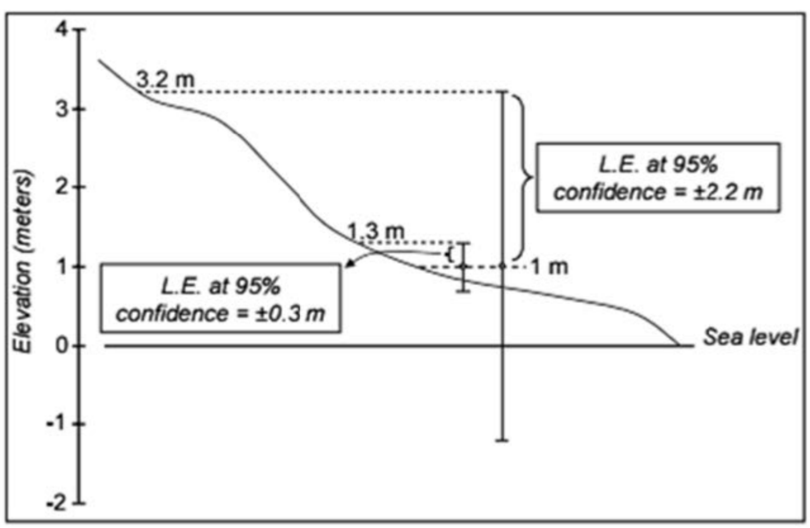


Figure 9. *illustrates how the uncertainty of elevation data affects the delineation of coastal elevation zones, including the hypsometry of storm surges. In this example, a sea level rise of 1 meter is mapped onto the land surface against two elevations (Gesch, 2009).*

accuracy of digital elevation data is fundamental vertical accuracy, which describes vertical accuracy at the 95 percent confidence level in open terrain where errors should approximate a normal error distribution (Heideman, 2014). As of this guidebook's publication, the fundamental vertical accuracy for the current best available LiDAR data tends to be +/- 0.135cm in the vertical. Hence, this imposes a limitation on the inundation modeling.

Handling Error and Uncertainty in DEMS and Models

The NOAA SLOSH model contains inherent uncertainty owing to the coarse resolution of the model grid. Allowing for this, and as a conservative approach, this research rounded interpolated values to the highest adjoining SLOSH cells for areas that SLOSH did not characterize as flood cells. The impact of positional error in the LiDAR digital DEM was considered during the analysis of the potential for recurrent tidal flooding. This was accomplished through iterative Monte Carlo (MC) error distribution modeling (Liu et al. 2007). An MC error distribution model was created to generate 100 unique permutations of the DEM for the study area, using a pseudo-random number generator and the bounds of potential error. The model follows the current practice of sea level rise mapping which assumes that LiDAR vertical errors follow a normal distribution with zero bias (Cooper et al., 2013). Similar methods were used by Liu et al. (2007) for studying the effect of elevation error on shoreline position and Bodoque et al. (2016) for characterizing first-floor elevation errors related to flood modeling.

Freeboard Elevation Analysis

Where infrastructure or other assets have elevation values above ground level, you can calculate freeboard, or the vertical difference above, or submergence below, a given flood height. Freeboard elevations can then be estimated and ranked or evaluated for impacts. For example, FEMA's HAZUS level 3 advanced impacts use depth-damage curves to predict potential damage. Having freeboard data can refine potential risk and damage assessments. Another important consideration in combining multiple sources of GIS data with elevation is the need to adopt a uniform vertical datum and units. More often than not, LiDAR and elevation surveys are done in feet above the NAVD88 vertical datum. However, storm surges and coastal hydrographic data oftentimes reference a tidal datum (e.g., mean higher high water, mean sea level, or mean tide level.) Historical coastal elevations may even reference past tidal epoch datums, which are averaged every 19 years. To ensure co-registered vertical and elevation datums are used, careful examination of metadata and potential adjustments are sometimes required. A widely accepted tool for vertical datum and unit adjustments is NOAA's VDATUM tool. Additional information can be found at NOAA's Digital Coast, and FEMA

Vertical Datum. One may be able to avoid these adjustments by identifying a desired horizontal and vertical spatial reference before assembling geospatial data. Many of the aforementioned LiDAR repositories, for instance, offer options to select among various spatial and vertical references in their interactive download tools. Even after following such parameters, one should also undertake spot checks between data, looking for gross errors in the spatial alignment and vertical values.

Nuisance Tidal Flooding

For tidal flooding, also called nuisance or recurrent flooding, we retained the NOAA threshold value local to the area based upon the local elevation of street-level impacts. Nonetheless, as tidal flooding increases in frequency, potentially non-linearly with sea level rise, today's nuisance or extreme becomes tomorrow's mean (Sweet and Park 2014.) The rate of occurrence of nuisance events is increasing along the East Coast, such that nuisance events are becoming chronic, and tipping points for impacts in areas such as Charleston, South Carolina, where relative sea level rise rates are themselves faster than other areas.

The number of days of tidal flooding is expected to increase in pace with rising sea level. Indeed, in Charleston, the number of days with tidal flooding increased to 50 in 2016 (Figure 10) and the rise is expected to continue.

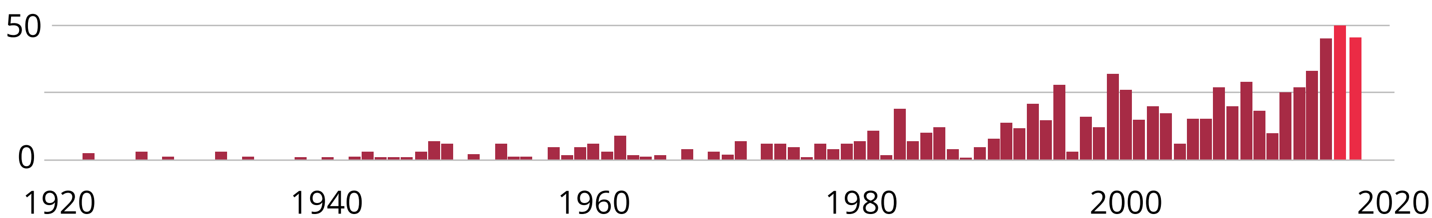


Figure 10. *Days with flooding by year due to higher tides associated with sea level rise in Charleston, S.C. Runkle, et al., 2017. Updates from NOAA, 2018.*

STEP 5 Using the Susceptibility Index (SI)

a. U.S. Army Corps of Engineers (USACE) 4x4 Resilience Matrix (RM)

Many of our traditional risk assessment tools still focus primarily on evaluating known (predictable) stresses to physical infrastructure and health networks. This approach has proved inadequate to ensure continuity in our complex real world full of uncertain threats and dynamic change. Communities are recognizing that climate and resulting weather patterns are changing. Sea levels are rising. Because one of the aims of this project was to provide coastal decision-makers with a tool that can be used to quickly assess and respond to public health impacts in urban environments in light of changing and sometimes, unanticipated climate impacts, the USACE RM was chosen and modified to measures resilience. The RM framework, consists of a four-by-four matrix in which the columns of

	Prepare	Absorb	Recover	Adapt
Physical	Is this sector physically prepared for an extreme event? Are there emergency stockades or weather resistant construction?	Can this sector continue "normal" operation in spite of radical environmental changes? Is this sector designed to function over a range of scenarios?	Would you expect this ector to rapidly rebuild damaged infrastructure, or quickly regain impaired functionalities?	Would you expted this sector to phase out obsolete assets, update equipment, and look for novel system configurations basd on lessons learned?
Information	Does this sector have pre-existing knowledge or protocols prepared for extreme events?	Would you expect this sector to rapidly take in information and respond effectively during an event?	Can this sector identify / prioritize system components that need remediation? Does this sector have a way to retrieve data that may be loset during an extreme event?	Does this sector use collected information / data from internal or external sources to forecast future scenarios? Would you expect this sector to conduct risk analysis?
Cognitive	Is this sector "mentally and emotionally prepared" to deal with the contigencies presented by an extreme event?	Does this sector react well under pressure? Would you expect this sector to make sound decisions during stressful events?	How would you decsirbe the "morale" of this sector following an extreme event? Would thi individuals composing this sector quickly return to standard operating procedures?	Would you expect an extreme event to leave a "lasting impression" on the individuals in this sector? Would this sectors percieved risk change following an extreme experience
Social	Has this sector communicated its role and capacity during an extreme event? Does this sector have predefined channels of communication for extreme events?	Would this sector supply direction / authority to individuals seeking stability during times and turmoil?	Would this sector coordinate with public/private entities to deliver aid or restore damaged assets?	Would this sector incentivize its customers, constituents, and/or stakeholders to implement more resilient practices?

Figure 11. *The Resilience Matrix Framework, 4x4 Matrix (Fox-Lent, 2015).*

the matrix correspond with the four stages of the disaster cycle (preparation, absorption, recovery, and adaptation), while the rows correspond to the four domains of a complex system (physical assets, information, cognition, and social structure) (Figure 11).

This project attempts to predict susceptibility to health impacts from flooding of water, waste water, and transportation infrastructure by using assessments of resilience and vulnerability.

If susceptibility is the degree to which a system is open to damage, vulnerability is the degree a system is exposed to a hazard, and resilience is the capacity to negate negative outcomes, then our simple formula is:

(S) Susceptibility = (V) Vulnerability – (R) Resilience.

The exercise we lay out uses the U.S. Army Corp of Engineers (USACE) Coastal Community Resilience Assessment (Fox-Lent, Cate & Linkov, 2015) to assess resilience, and a vulnerability assessment, (using the GIS analysis) to determine susceptibility of each sector through each phase of the disaster cycle. The spreadsheet tool available from the S.C. Sea Grant Consortium website (and video to assist in conducting these assessments) will leave participants with identified best management protocols to help their community decrease their susceptibility to these flooding impacts.

Using the spreadsheet, the intersection of each row and column contains a question about capacity that prompts the user to rate the cell on a scale of one to five, with one representing a low capacity and five representing the highest possible capacity (Figure 12). To complete

Hospital System				
	Prepare	Absorb	Recover	Adapt
Physical	4	4		
Information	4	3		
Cognitive	3	3		
Social	3	3		

Water System / Utility Network				
	Prepare	Absorb	Recover	Adapt
Physical				
Information				
Cognitive				
Social				

Lowest Capacity	1
Low Capacity	2
Med Capacity	3
High Capacity	4
Highest Capacity	5

Municipal Gov / Emg Response				
	Prepare	Absorb	Recover	Adapt
Physical				
Information				
Cognitive				
Social				

Local Population				
	Prepare	Absorb	Recover	Adapt
Physical				
Information				
Cognitive				
Social				

Figure 12. *The Resilience Matrix Framework, 4x4 Matrix Inputs.*

this section, the user will develop a score use the benchmarking tool in the adjacent tab which will allow them to select the best management protocols that are currently in place. The score is then transferred to the 4X4 matrix.

At the end of the assessment, the matrix can be color coded or summated, allowing

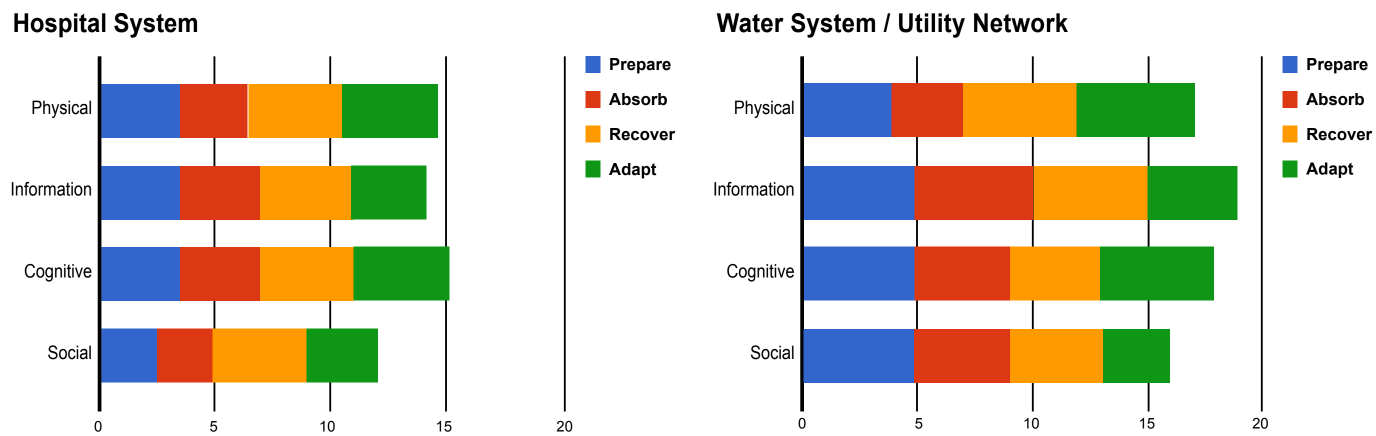


Figure 13. *Graphical Outputs from the Resilience Matrix 4x4 Framework.*

individuals and organizations to quickly recognize their strengths and weaknesses for a given event. The process can be repeated for multiple organizations, and the scores can be combined or compared. The example in Figure 12 shows a health care network with a higher capacity to recover or adapt compared to its capacity to prepare or absorb. With this information in mind, the health care facility that completed this indexing exercise may want to focus on activities aimed at preparing the hospital for an emergency event before it happens, especially with respect to social components (social-media presence, interagency emergency drills, designated public information officers, etc.).

This framework is flexible, which comes in handy when practitioners from different disciplines employ their own meanings and terminologies for vulnerability, susceptibility, and resilience. In addition, extreme weather events tend to cross organizational boundaries and force collaboration; this methodology allows users to assess preparedness from the perspective of an individual organization as well as from the perspective of a group of organizations (Fox-Lent et al., 2015). A video discussion of conducting the Susceptibility Assessment, including the component parts and a copy of the interactive spreadsheet can be found on the S.C. Sea Grant Consortium website. Both are helpful in preparation and review. The spreadsheet can be adapted to meet the needs of specific communities.

b. Susceptibility self-assessment (combining the 2x2 and 4x4)

In addition to the USACE 4x4 resilience matrix, a 2x2 vulnerability matrix was created to keep track of visually interpreted hazards. To use the 2x2 matrix, GIS maps with varying degrees of sea level rise, storm surge, and/or rainfall are overlaid with critical infrastructures (hospitals, fire departments, schools, evacuation routes, etc.) and examined for inundation. The columns of the 2x2 vulnerability matrix are comprised of Inundated/Not Inundated, while the rows of the matrix are labeled Compromised/Not Compromised (Figure 14).

As participants view maps of their jurisdiction overlaid with potential storm scenarios, they may notice inundation in critical areas. These participants will then use the 2x2 table to indicate the degree to which the infrastructure of interest is compromised. For example,

Hazard Scenario:

☐ Nuisance Flooding ☐ Rainfall + Nuisance Flooding ☐ Cat 1 ☐ Cat 2 ☐ Cat 3

Sector: ☐ Water Infrastructure ☐ Healthcare System ☐ Municipal Government ☐ Population

Layer: ☐ Sewage Treatment Facilities ☐ Sewer Lines ☐ Water Treatment Facilities ☐ Water Lines ☐ Wells ☐ Hospitals ☐ Home Health Services ☐ Medical Centers ☐ Nursing Homes ☐ Population Density

Area: ☐ Peninsula ☐ West Ashley ☐ James Island

	Inundated	**Not Inundated**
Compromised	Coverage/Score: Notes: (i.e., exposure, length of time, etc.)	Coverage/Score: Notes:
Not Compromised	Coverage/Score: Notes:	Coverage/Score: Notes:

Impact Scoring Rank:

A: No impact, full function
B: Sporadic or partial disruption of service, local outage, nominal damages
C: Partial service disruption, localized functions offline
D: Widespread service disruption, multiple core segments offline or damaged
E: Complete service disruption, emergency declared, long-term impact

Figure 14. *2x2 Vulnerability Matrix.*

during workshop events in Charleston, participants were shown an inundation map of the city during a Category 1 hurricane with antecedent rainfall. According to GIS projections, if Charleston were hit by a Category 1 hurricane, many health care facilities and their access roads located along the Ashley River would be inundated. Workshop participants examined the total number of hospitals in the city, visually estimated the percentage of hospitals experiencing inundation, and recorded that percentage in the box labeled inundated (Figure 15). The amount of inundation Charleston would face should it be exposed to a Category 1 hurricane would likely render most of these facilities in a state of compromised operations. The extent to which the facility is compromised is also recorded in the appropriate box. However, instead of reporting a percentage, the level to which the facility is compromised

Hazard Scenario:

☐ Nuisance Flooding ☐ Rainfall + Nuisance Flooding ☐ Cat 1 ☐ Cat 2 ☐ Cat 3

Sector:
- ☐ Water Infrastructure
- ☐ Healthcare System
- ☐ Municipal Government
- ☐ Population

Layer:
- ☐ Sewage Treatment Facilities
- ☐ Sewer Lines
- ☐ Water Treatment Facilities
- ☐ Water Lines
- ☐ Wells
- ☐ Hospitals
- ☐ Home Health Services
- ☐ Medical Centers
- ☐ Nursing Homes
- ☐ Population Density

Area:
- ☐ Peninsula
- ☐ West Ashley
- ☐ James Island

	Inundated	**Not Inundated**
Compromised	Coverage/Score: **Coverage** - 85% of hospitals appear inundated to a degree that would imply system failure **Score** - The level of inundation at these facilities is so great one would expect a complete or near complete shutdown as in description(s) "D" and "E" Notes: (i.e., exposure, length of time, etc.)	Coverage/Score: **Coverage** - 5% of hospitals are not inundated but may face compromised operations due to logistics **Score** - the level of inundation at these facilities is negligible, however, functions may be impaired by power outages, water shortages, and transportation complications, as in description "C" Notes:
Not Compromised	Coverage/Score: **Coverage** - 5% of hospitals appear inundated but not compromised **Score** - the level of inundation at these facilities may impede function, but not in a severe capacity as in description "B" Notes:	Coverage/Score: **Coverage** - 5% of hospitals are not inundated, nor are they compromised **Score** - there is no inundation at this location, and the facilities in this category are still accessible and functional as in description "A" Notes:

Impact Scoring Rank:
A: No impact, full function
B: Sporadic or partial disruption of service, local outage, nominal damages
C: Partial service disruption, localized functions offline
D: Widespread service disruption, multiple core segments offline or damaged
E: Complete service disruption, emergency declared, long-term impact

Figure 15. *2x2 Matrix - Hospital inundation under a Category 1 Hurricane with antecedent rainfall.*

is reported using a five-point scale system where A represents full functioning and E representing a complete closure of all services (Figure 16). Since both the 4x4 resilience matrix and the 2x2 vulnerability matrix operate on a five-point scale, it is possible to combine the two assessments to infer susceptibility by defining it as the difference between vulnerability and resilience.

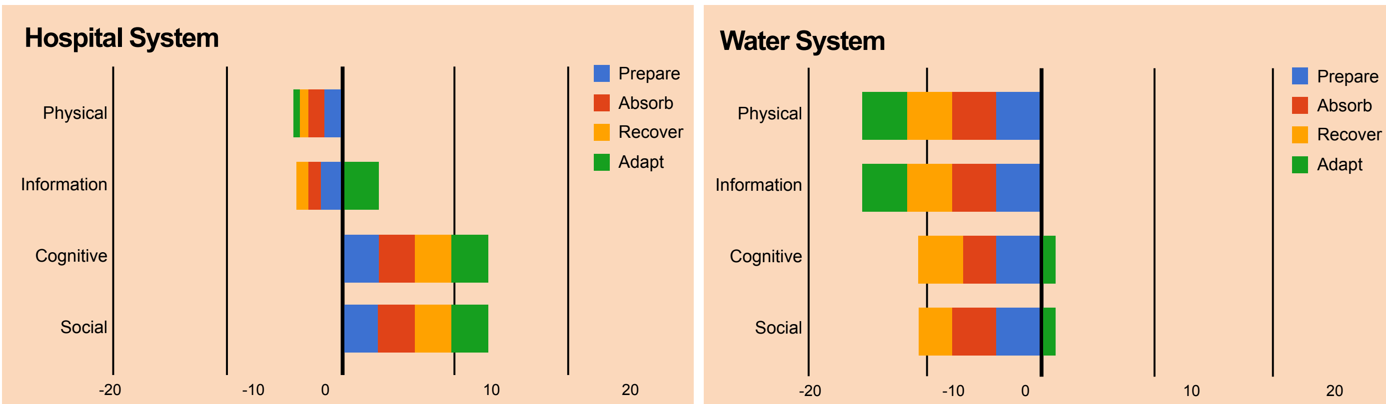


Figure 16. *2x2 graphical examples of susceptibility following a tabletop exercise in Charleston, S.C. (2017).*

Coverage	Score
100%	A ▾

Suggested Vulnerability Score 1

Impact Scoring Rank

(1) A: No impact, full function
(2) B: Sporadic or partial disruption of service, local outage, normal damages
(3) C: Partial service disruption, localized functions offline
(4) D: Widespread service disruption, multiple core segments, offline or damaged
(5) E: Complete service disruption, emergency declared, long-term impact

Figure 17. *Calculating vulnerability scores using the 2x2 matrix process.*

With this formula in place, **low or negative susceptibility is desirable**, since positive numbers would indicate vulnerability scores greater than resilience scores (Figure 17).

1. The spreadsheet output provides susceptibility scores for each sector as well as separate resilience, vulnerability and disaster-phase capacity scores for each sector (Figure 18).

2. To assist in assessment and improvement, the output provides each sector with a percentage score above or below average for physical, information, cognitive and social resilience as well as a list of best management practice protocols (those unchecked in the exercise) to improve resilience (Figure 19).

Assessing your community's resilience, vulnerabilities, and susceptibilities is critical in reducing public health and infrastructure risk posed by extreme weather and events. However, in addition to discussing and quantifying risk, actions must be taken and initiatives must be put

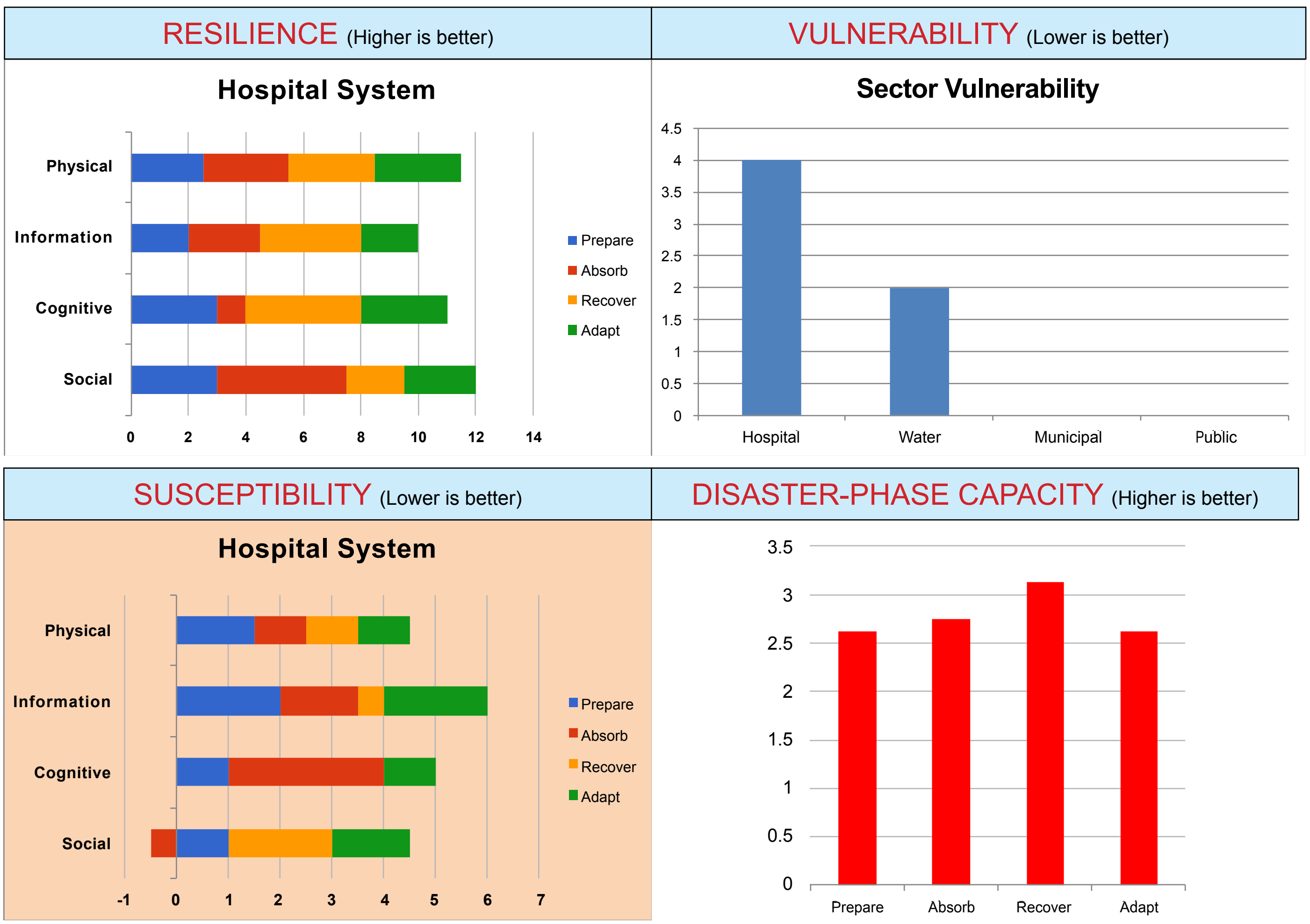


Figure 18. *The spreadsheet output (example provided) identifies susceptibility scores for each sector as well as separate resilience, vulnerability and disaster-phase capacity scores for each sector.*

Water Utility

	Percent Above or Below Average Susceptibility			
	Prepare	Absorb	Recover	Adapt
Physical	- 1.00%	41.67%	20.33%	20.33%
Information	9.67%	20.33%	20.33%	- 1.00%
Cognitive	41.67%	- 1.00%	20.33%	20.33%
Social	20.33%	41.67%	41.67%	20.33%

unchecked protocols

Water Utility

PHYSICAL PREPARE
Identify and evaluate bulk sludge transport and disposal options
Maintain Provisions of non-perishable food, water, and resting quarters for employees that must remain on the job for extended hours during emergencies
Provide transportation, communication equipment, mechanical tools, maintenance equipment, fuel, and medical services for incident management personnel
Ensure that critical equipment can be operated by using alternative power sources: IE ensure generator is powerful enough to sustain operation of heavy machinary / high pressure pumps
Where fiscally feasible, maintain backups of critical and mechanical equipment. (Spare life station pumps, electrical starters, breakers, relays, SCADA transmitters)
Ensure there are surplus decontaminants resources (chlorine, UV bulbs, sulfer dioxide, sodium hydroxide, etc.) on hand
PHYSICAL ABSORB
Water facility utilizes electronic systems to detect, monitor, and alert staff of contamination incidents
Coordinates the delivery of emergency drinking water with government staff to areas that have lost water services
Water utility runs grit and screenings removal continuously during high flow events
If possible, bypass affected lines to minimize spillage during waste/storm water overflows.
Water facility utilizes onsite/oncall electricians to operate high voltage/current generators and or replace equipment with advanced circuitry.
“Large” chlorine gas operations have prepared an alternative method to feed chlorine into local infrastructure.
PHYSICAL RECOVER
Survey and assess damage, list repairs needed, estimate work times, and communicate downtime with municipal government
Water facility maintains detailed documentation of repairs, reconstruction, and replacement at damaged locations
Utility holds an individual or team responsible for rapidly accessing documentation required for (re)construction permits
Equipment motors are dried out and re-lubricated after any overflow event. Other equipment are checked for water / mechanical damages.

Figure 19. *The output (example provided) affords each sector with a percentage score above or below average for physical, information, cognitive and social resilience determined in this exercise, as well as a list of best management practice protocols (those unchecked in the exercise) to actively improve resilience for the future.*

into practice. Improving resilience and reducing vulnerability relies heavily on the execution of adaptive measures. It is highly unlikely that you will see increased resilience or a decrease in susceptibility without implementing new protocols into the processes of your community or organization. In this process best management practices and standard operating procedures sourced from regional emergency operation protocols to benchmark our local operations with similar organizations and communities.

Remember, the last two steps of a resilience assessment – developing courses of action and implementing adaptation measures (Figure 8) – are absolutely critical to reducing susceptibility. A video discussion of conducting the Susceptibility Assessment including the component parts and a copy of the interactive spreadsheet can be found on the S.C. Sea Grant Consortium project page. Both are helpful in preparation and review. The spreadsheet can be adapted to meet the needs of specific communities.

Project Outputs

- Visualization of critical infrastructure to assess vulnerabilities
- Quick and easy decision-making tool for public health and government officials, as well as municipalities
- Use of current projections and cutting-edge technologies to make evidence based decisions

Platform for communication amongst sectors

- Unique opportunity for water infrastructure, power officials, healthcare providers, emergency managers to come together and discuss links among the sectors
- Recognition that many vulnerabilities may lie between the sectors, instead of within the silos

Created a cohesive response to emergency events

- Opportunity to discover out-of-the box solutions and improve communication and coordination among sectors
- Development of interdisciplinary best practices to reduce water infrastructure vulnerabilities nationwide
- Open communication pathways

Conclusions

We acknowledge that this GIS-based Susceptibility Index cannot and should not replace any current planning or preparedness measures that are being implemented by our stakeholders, such as trainings, exercises, or community outreach. However, the hope is this SI will be used to strengthen those actions through identification of vulnerabilities, effective communication, and coordination of response to future climate pressures.

The susceptibility exercises outlined in this document are intended to serve as a blueprint for your own local assessment methodologies. Information from these kinds of assessments are paramount in understanding the unique hazards faced by your locality, but remember that knowing is only half the battle. In addition to proposals and plans, preventative actions must be put into practice by water utilities, health care networks, municipal governments, and individual residents alike because the costs of inaction are too high.

Additional Resources and Appendices

Federal Emergency Management Agency (FEMA)

FEMA Hazard Mitigation Grant Program – The Hazard Mitigation Grant Program provides grants to implement long-term hazard mitigation measures after a major disaster declaration. The purpose of the program is to reduce the loss of life and property due to natural disasters and to enable mitigation measures to be implemented during the immediate recovery from a disaster.

FEMA Pre-Disaster Mitigation Program – The Pre-Disaster Mitigation Program provides funds for hazard mitigation planning and the implementation of mitigation projects prior to a disaster.

FEMA Coastal Construction Manual

U.S. Department of Housing and Urban Development

Community Development Block Grant Program – The Community Development Block Grant program provides communities with resources to address a wide range of unique community development needs, including disaster recovery assistance.

U.S. Environmental Protection Agency

Clean Water State Revolving Fund

Drinking Water State Revolving Fund

Public Notification Rule Quick Reference Guide

Funding Sources for Small and Rural Water-Systems

Other Governmental Agencies

Emergency System for Advance Registration of Volunteer Health Professionals – This is a state-based electronic database of healthcare personnel who volunteer to provide aid in an emergency. The program is managed through the U.S. Department of Health and Human Service.

Assistant Secretary for Preparedness and Response: Healthcare Recovery Planning Guide

US Department of Agriculture: Rural Utility Service, Water and Waste Disposal Program

National Hurricane Center (NHC): Outreach Materials / Resources

Substance Abuse and Mental Health Services Administration (SAMHSA): Disaster Specific Resources

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