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Contents

Foreword
Geoff Scott and Paul Sandifer 1

The Road to Resiliency for South Carolina Water Utilities Paved by Planning, Persistence, and Careful Navigation of Realities and Hypotheticals
Kaleigh Sims, Megan Copsey, and Chris Ericksen 3

“I Won’t Use the Term Dumbing It Down, but You Have to Take the Scientific Jargon Out”: A Qualitative Study of Environmental Health Partners’ Communication Practices and Needs
Katya Altman, Brooks Yelton, Hildehardo F. Viado, Jr., Margaret A. Carson, Louisa Schandera, R. Heath Kelsey, Dwayne E. Porter, and Daniela B. Friedman 11

NPDES Phase II Stormwater Rule—Integrating Community Engagement and Engineering Education
Monica Gray 33

South Carolina Sampling, Analysis, and Governance of Per- and Polyfluoroalkyl Substances
Justin Kidd, Emily Fabricatore, and Dennis Jackson 48

Identification of Stormwater Pollution Hotspots in Charleston Peninsular
Ashleigh Kirker and Vijay M. Vulava 54

Enterococci Contamination on Edisto Island, South Carolina: Frequency, Sources of Contamination, and Prospects on How to Improve Water Quality
Christina Ek, Dwayne E. Porter, David Graves, Bryan Rabon, Bo Cai, Guoshuai Cai, Ronald Willis, and Geoffrey I. Scott 68

Widespread Contamination of Polychlorinated Biphenyls in South Carolina and North Carolina (USA): A Legacy of Malarial Eradication and Mosquito Control
James B. Glover and Deke T. Gundersen83

Health Communication Blindspot: A Case Study of Harmful Algal Blooms in the South Atlantic States
Jaron King98

Foreword

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The *Journal of South Carolina Water Resources (JSCWR)* is dedicated to scientific research and policy to meet the growing challenge of providing water resources for the sustainable growth of South Carolina's economy while preserving its natural resources. This special issue focuses on Water Quality and Public Health and is sponsored by the federally funded Center for Oceans and Human Health and Climate Change Interactions (COHHC²I) at the University of South Carolina (UofSC). In addition to UofSC researchers, the COHHC²I involves researchers, students, and other participants from Baylor University, The Citadel, College of Charleston, Rutgers University, University of Maryland's Center for Environmental Science, and the Lowcountry Alliance for Model Communities and Interstate Shellfish Sanitation Conference.

Coastal shoreline counties—those that border directly on ocean or Great Lakes waters or are subject to tidal flooding—make up less than 10% of the contiguous US land area (excluding Alaska) but are home to about 40% of the population. When we include the next immediate tier of counties, termed by the National Oceanic and Atmospheric Administration (NOAA) as coastal watershed counties, approximately 53% of the population lives in a narrow band along our Atlantic, Pacific, Gulf of Mexico, Caribbean, and Great Lakes coasts that comprises less than 20% of the US landmass. Not surprisingly, population density is 3 to 4 times higher on the coast than the average in the rest of the country, and the economic and societal values of both natural and built infrastructure and the populations, businesses, tourism, and quality of life they support, are immense. In South Carolina, the coast is the major economic engine of the state, not only from the standpoint of the tourism industry but also as the location of ports essential to our industrial and commercial operations and as an attractant for many new residents. Over many centuries, large concentrations of people have been drawn to coastal areas, resulting in most major cities being located there, and they continue to be “people magnets,” as recent population trends confirm. Yet, these areas are also fragile and subject to various hazards. Along with climate change, which presents truly existential threats, other rapidly intensifying concerns relate to water quality and public health. At dire risk from these threats are high quality potable water essential for human life and safe waters for recreation and the biodiverse ecosystems that define our invaluable coastal quality of life.

Oceans and Human Health (OHH) is now a widely recognized “meta-discipline”; that is, a collection of multi- and inter-disciplinary endeavors that brings together experts from numerous fields to focus on complex societal problems that no one discipline can address effectively. Scientists and practitioners from domains such as oceanography, marine biology, ecology, climatology, biomedical science, environmental health science, medicine, public health, computer science and modeling, communication, psychology, and more pool their expertise to address water quality problems. Such problems include HABs (harmful algae blooms) and their toxins, naturally-occurring *Vibrio* bacteria, the growing problem of plastic pollution, and increasingly significant risks to human health, both singly and in combination and as exacerbated by climate change factors such as rising temperatures and seawater levels, changes in precipitation patterns, and increased coastal flooding. The COHHC²I receives support through a five-year grant from the National Institute of Environmental Health Sciences of the US National Institutes of Health. Tackling these issues requires robust interdisciplinary scientific approaches combined with equally strong engagement with affected communities to increase public environmental health literacy.

The eight articles in this special issue cover a range of topics and include communication of HABs health risks, South Carolina's legacy water contamination with PCBs, significantly polluted coastal urban stormwater hotspots in Charleston, PFAS pollution in drinking water, effective stakeholder-engaged research translation and communication about sea level rise impacts on water-borne health risks, sources and management of fecal bacterial contamination on Edisto Island, the resiliency of SC water utilities, and integration of community and student engagement in non-point source pollution prevention, source water protection and treatment, and innovative stormwater management practices. Students are primary authors for fully half of the articles, highlighting our efforts to develop young scientists. They are leading the development of new technical information and public engagement and translating scientific information into vital products for communities. Their efforts will assist in informing the public and help reduce OHH public health threats associated with climate change. We hope you find this issue stimulating and informative.



The Road to Resiliency for South Carolina Water Utilities Paved by Planning, Persistence, and Careful Navigation of Realities and Hypotheticals

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Abstract. Planning for a resilient future from known and emerging threats is a topic of interest among many organizations, especially in the utility sector. South Carolina communities depend on reliable and safe sources of drinking water and generally do not anticipate interruptions or issues with their water providers. With the rate at which the state is growing, the dependency will only increase. SynTerra worked with five utilities in South Carolina to assess their risk and resilience and develop or update emergency response plans. This paper reports on key takeaways from this experience in an effort to provide guidance on lessons learned to work toward a resilient future. The overall purpose of this paper is an effort to provide a firsthand account of how assessments and plans can be used as a guide for continuous improvement toward resiliency, with an ultimate goal of protecting human health.

INTRODUCTION

Most of us associate resilience with positive attributes and successful outcomes. We want to be resilient people with resilient systems. Being resilient, as defined by Merriam-Webster (2021), means “tending to recover from or adjust easily to misfortune or change.” To achieve resiliency, we must first identify the potential “misfortune” or “change” that could occur.

When we talk about resiliency of water utilities, we often focus on updating infrastructure. Undoubtedly, infrastructure is a key element of protecting the utility and human health from potential threats, but there is much more to establishing a truly resilient utility. The focus should not be exclusively on infrastructure; rather, the focus should be on addressing multiple elements of a water utility, including technical, organizational, social, and economic considerations (Pagano et al. 2017). Failing or aging infrastructure, outdated or nonexistent plans, ill-managed or limited budgets, poor public communication, and lack of education and training can all lead to vulnerabilities at a public water utility (Alva-Lizarraga et al. 2013). Understanding your utility’s strengths and weaknesses and incorporating new strategies into a plan can better position the utility to handle natural or humanmade disasters.

With the emergence of new threats to South Carolina utilities, whether from a new source, an unforeseen pandemic like COVID-19, or ever-changing climatic disturbances, it is essential for utilities to set a plan in action to withstand or recover from threats. Planning for future and enduring water utility resilience can be a tedious task filled with hypothetical scenarios, budget analysis, and tabletop exercises, all of which result in a substantial and complex document that might sit on a shelf or data server for years. Nevertheless, the exercise of performing a risk and resilience assessment (RRA) and updating or developing an emergency response plan (ERP) can provide tools that help the utility protect customers in the future.

BACKGROUND

With the US Environmental Protection Agency’s (US EPA’s) issuance of the 2018 America’s Water Infrastructure Act (AWIA), most water utilities should already be working on or have a completed RRA and ERP in place for the next 5 years. The legislation was enacted to improve drinking water quality, deepen infrastructure investments, and enhance public health and quality of life.

The objective of an RRA is to evaluate the vulnerabilities, threats, and consequences to a utility from potential hazards (US EPA 2019a). Or, in terms of resilience, the objective is

to identify the potential “misfortune” or “change” that could negatively affect the utility.

The 2018 AWIA legislation presented utilities with the opportunity to use a regulatory requirement for ongoing risk management, which proactively supports utility operations. The American Water Works Association (AWWA) published the J-100-10(1) (J-100) standard to help utilities meet the requirements of this legislation, but in reality, it established a framework for the aforementioned ongoing utility risk and resilience management. The key advantage to this process is that the evaluation takes the abstract concepts of vulnerability and risk and turns them into a quantifiable metric, allowing the utility to identify areas of improvement and make targeted modifications. To date, SynTerra, a science and engineering consulting firm headquartered in South Carolina, assisted 5 water utilities in South Carolina of varying sizes, from 15,000 to 400,000 people in their service population, to accomplish risk assessments and develop or update ERPs. While these documents often feel like a shelf placeholder, they contain valuable information, much of which should be put into practice to establish enduring resiliency and protect human health in the future.

ASSESSMENT METHOD

To facilitate the assessment, SynTerra conducted 5 to 6 workshops for the RRA and 2 to 3 workshops for the ERP, depending on the amount of information needed for each drinking water utility client. SynTerra followed the basic steps outlined in the AWWA J-100 standard for the RRA, the AWWA M19 Emergency Planning for Water and Wastewater Utilities document (Gay et al. 2018), and the USEPA Community Water System ERP Template and Instructions (US EPA 2019b) for the ERP. SynTerra chose a facilitated workshop approach that aligned with the complex nature of information-gathering required for RRA and ERP completion. The utilities had 3 to 10 employees present at each workshop. Upper-level management was present during each workshop, along with personnel from different departments (treatment plant, distribution line, public relations, etc.) to allow for viewpoints from various perspectives within the organization. SynTerra’s assessment team consisted of 2 to 3 personnel with experience in water, wastewater, or planning.

Because assessment information is dense and many abstract concepts are discussed, it is beneficial to take “small bites” and give everyone plenty of time to digest topics and details. Prior to a workshop, SynTerra’s assessment team sent meeting materials to the clients as needed to help facilitate the discussion in the workshop. During the workshop, SynTerra provided workshop-specific handouts to help the client follow along with the presentation and exercise. SynTerra also facilitated exercises to help engage the utility in the discussion. Once a workshop concluded, SynTerra’s

assessment team sent workshop deliverables to the client, which included meeting minutes, completed tables based on information from the workshop, follow-up questions, or requests for missing information. A stepwise approach using facilitated workshops over a year provides the opportunity to modify information as necessary during the process. Figure 1 demonstrates the general approach SynTerra took to conduct workshops and complete RRA and ERP reports.

To assess risk in terms of a dollar amount for the RRA and to determine a utility resilience baseline, SynTerra used both the US EPA’s Vulnerability Self-Assessment Tool (VSAT 2.0) and the AEM Corporation’s Program to Assist Risk and Resilience Examination (PARRE). These platforms helped facilitate discussions regarding consequences, countermeasures, likelihood, and vulnerability. Ultimately, using these tools provided additional aid for assessing overall risk and resiliency.

FINDINGS

The following section details SynTerra’s knowledge gained during the process. Using the J-100 standard as a reference, we compiled a few key takeaways for implementing risk, resilience, and emergency response in utility planning and management based on our experience.

RISK AND RESILIENCE ASSESSMENT

Key Takeaway 1: Involve a Diverse Team

The first and most critical takeaway of conducting an RRA and an ERP is the identification and involvement of utility personnel. Successful assessments are the result of collaboration between the key information centers of the utility. The utilities SynTerra worked with involved diverse teams by including personnel from all levels in each workshop. Typically, a workshop would include a few executive-level personnel, middle management, and a few employees from the line crew, treatment plant, maintenance, or other operations. Including personnel from all levels allowed for a more meaningful conversation about the system as a whole and provided broader perspectives on how to reduce the utility’s risk to malevolent or natural hazards.

Key Takeaway 2: Utility Resiliency Index (URI) Continuous Improvement

The second takeaway is the establishment of a utility resilience baseline using the URI. The URI is a risk-management tool that can assess a utility’s capability to respond to and recover from an incident affecting critical operations (AWWA 2010). The URI uses 12 indicators to calculate the index (Figure 2). The indicators are divided into two subsets: operational, which is the ability of the utility to react to and/or resolve various hazards that interrupt service; and financial, which

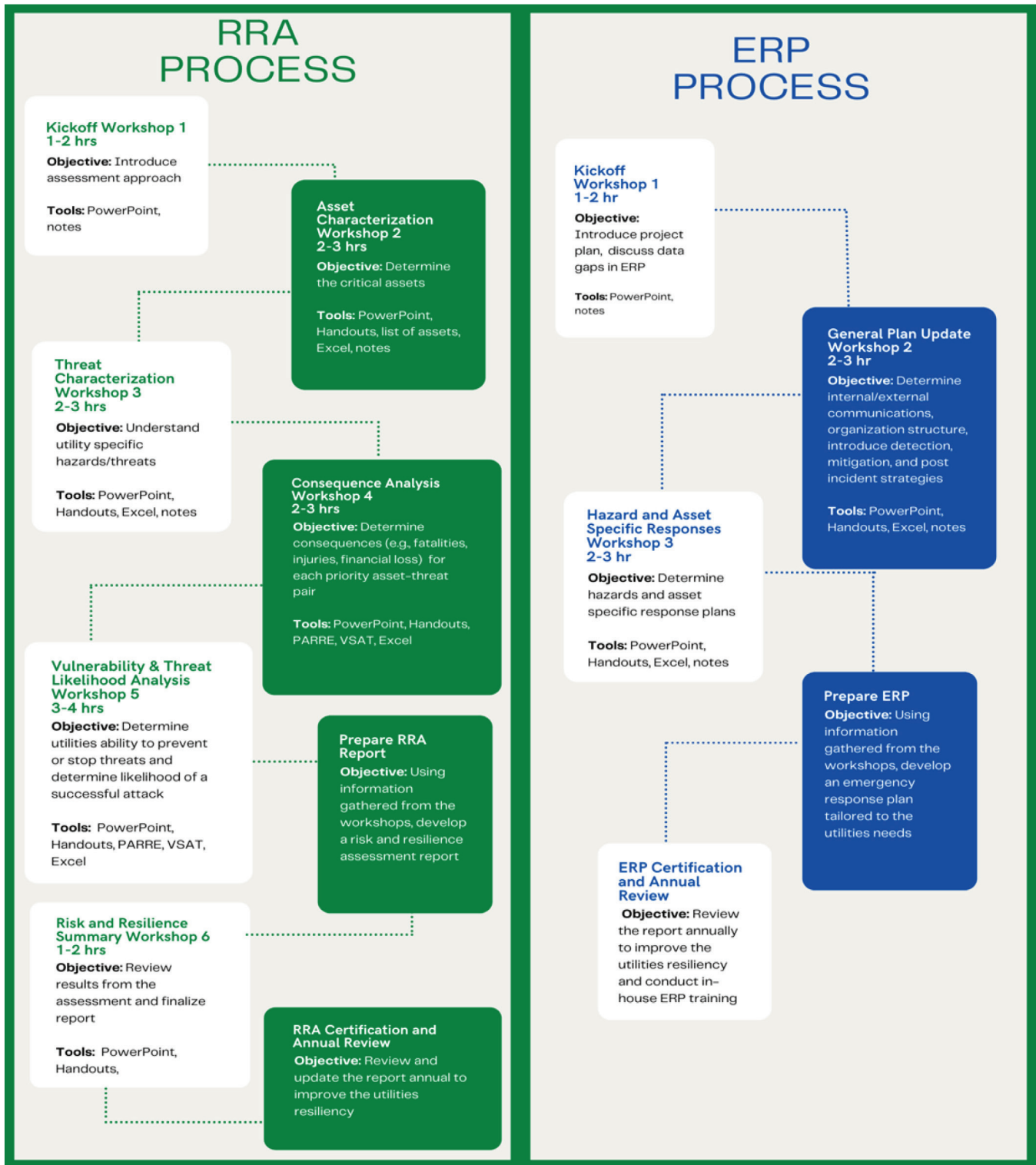


Figure 1. RRA and ERP processes.

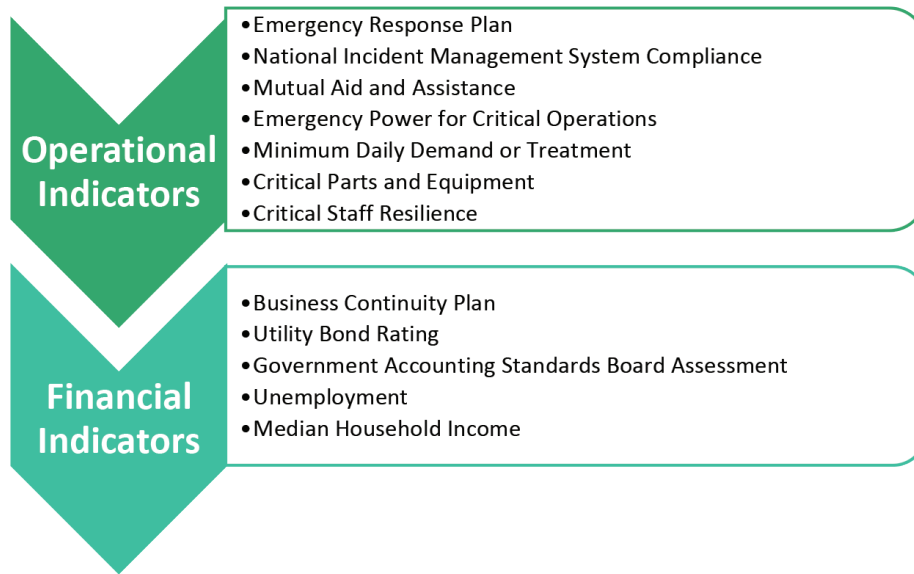


Figure 2. The 12 URI indicators.

is the ability of the utility and its service area to react to and/or resolve various hazards that may interrupt revenue to the utility.

Responses to the indicators are assigned values and weights, which are aggregated to provide a characterization of a utility’s resilience on a scale of 0 percent to 100 percent. A low URI score for a utility indicates a lesser capability to respond to and recover from an incident, while a high URI score indicates a greater capability to recover from an incident. Among SynTerra’s clients in South Carolina, URI scores ranged from 59 percent to 84 percent based on responses to the 12 indicators. During this process, SynTerra encouraged their clients to identify any areas of improvement to increase the URI score. Examples of improvement opportunities include: 1) pursuing National Incident Management System (NIMS) certification or 2) increasing cross-training among utility personnel to increase critical staff resilience (CSR). Implementing an annual review of the URI provides a reli-

able metric for understanding utility resilience, setting targeted goals for improvement, and easily measuring progress.

Key Takeaway 3: Revisit your Asset List

The third takeaway is the importance of ongoing asset management. Asset characterization is a step in the J-100 that lays the foundation for utility asset management. The objective of the asset characterization step is to determine the assets — physical, human, or informative — that are critical to utility operations. Arguably, every asset employed by the utility is critical because each asset supports utility operation. Therefore, using the utility mission statement or some other priority evaluation is important in determining which assets should be considered critical. In the RRA process, SynTerra used a priority evaluation system in conjunction with the utility mission statement to score the assets based on three categories (Figure 3):

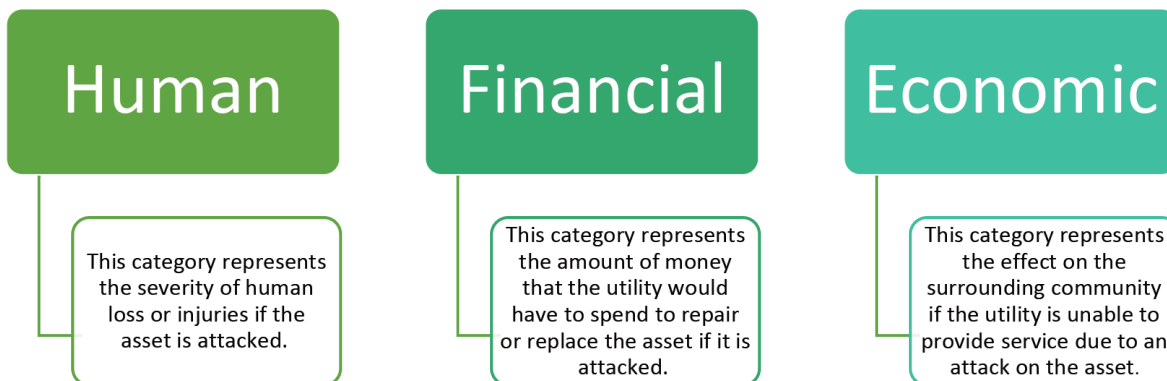


Figure 3. Three categories for priority scoring.

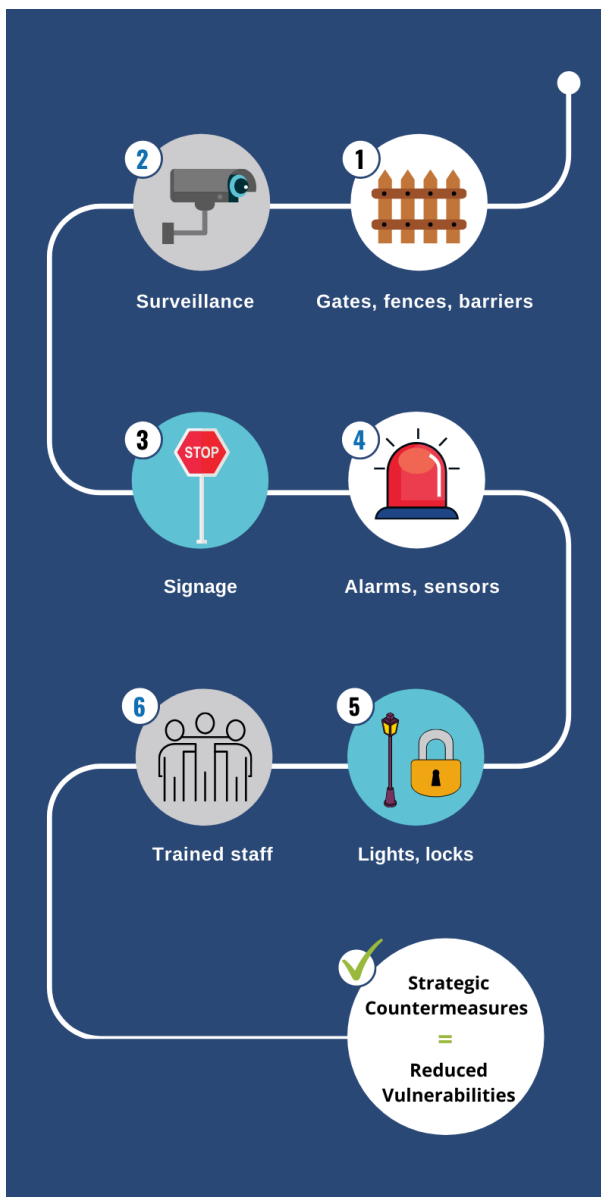


Figure 4. Countermeasure examples.

Implementing a management system that not only inventories assets in the system, but also their status and criticality to utility operations, will allow for consistent identification of utility vulnerabilities. Additionally, SynTerra recommends that utilities should conduct an annual review of an asset list using the priority evaluation, especially if new assets are added to the system. The annual review helps utilities with capital improvement planning because the assets already will be cataloged and prioritized.

Key Takeaway 4: Understand Your Vulnerabilities

The fourth takeaway for conducting a risk and resilience assessment is vulnerability analysis, which is another step in the J-100 standard. The objective of the vulnerability analysis step is to identify the vulnerabilities that would

allow a threat to be successful and cause the previously identified consequences, such as service outage or loss of life. The vulnerability, expressed as the vulnerability likelihood probability, represents a measure of both the effectiveness of an attacker/threat and of the countermeasures employed by the utility (AEM Corporation 2020). Countermeasures can be defined as the systems that are put in place to protect the utility’s critical assets. Countermeasure systems can be structural, such as a gate, or nonstructural, such as trained staff (Figure 4), and they typically lessen the consequence severity of a successful attack or event (AEM Corporation 2020).

Understanding utility countermeasures, how they are employed, and ways they can be improved is an important step in risk and resilience management. The J-100 standard presents risk as a dollar-valued amount based on the calculated vulnerability likelihood percentage. By understanding utility vulnerabilities, employed countermeasures, and available countermeasures for implementation, strategic countermeasure investments to increase utility resilience and decrease risk can be made.

After SynTerra identified countermeasures at each utility, it was recommended that they improve their countermeasures where possible. For example, if the utility did not have video cameras at their remote assets like pump stations, then installation of a 24/7 surveillance system was recommended to help reduce the success of a threat.

Key Takeaway 5: Update the RRA

Outdated or unused assessments and plans do not provide much of a benefit to a utility’s future resiliency and adaptability to changes.

Revisiting other steps in the J-100 standard, not explicitly discussed in this article, is beneficial for utility risk and resilience management. For example, threat characterization (a step in the J-100 process), which has the objective to determine the reasonable worst-case threats, natural hazards, and supply-chain scenarios, could be incorporated into the ongoing risk and resilience management. As the utility experiences new threats like changing climate patterns or increasing cyberattacks, it is recommended that asset-threat assignments be updated. Additionally, maintaining a relationship with the Local Emergency Planning Committee (LEPC) and other community stakeholders could aid in the identification of emerging threats. An annual review of events that occurred causing damage to the utility assets will also be beneficial for ongoing risk management and adaptive resiliency. Similarly, the consequences step in the J-100 process has the objective to determine what happens in the event of a successful threat and to define the consequences in terms of financial loss to the utility, fatalities, serious injuries, and economic loss to the regional economy. The J-100 standard approach monetizes anticipated consequences so that the

final risk number is presented as a dollar value. Understanding consequences as a dollar amount provides perspective for the actual magnitude of an event and sets the stage for eventual cost-benefit analyses on mitigation efforts.

Finally, if a new asset, countermeasure, or response to the URI indicators occurs, revisiting the risk assessment is recommended. That way, the utility has a better understanding of its current and future resiliency and can continuously improve on any newly identified gaps.

EMERGENCY RESPONSE PLANNING

One of the most effective ways to employ the results of the risk and resilience assessment is to develop, maintain, and train on the utility's emergency response plan. It is not possible to have a utility free of threats, which rings especially true after the events of 2020. Ensuring that your ERP is continuously reviewed and updated, and that staff members are properly trained on it, can help the utility respond to an unforeseen event. The ERP is a valuable source of information that helps utility employees know how to quickly and effectively respond in the event of a successful threat. Employing this plan and conducting regular training sessions with the appropriate employees will lessen the effect of humanmade or natural disasters on the utility, while also promoting employee and community safety and enhancing the ability to continuously provide safe and reliable drinking water to the community.

Similar to the RRA process, SynTerra worked with clients to develop updated ERPs through a series of workshops, in-person exercises, and follow-up reviews. SynTerra thoroughly evaluated the most recent ERP of each utility and identified any gaps or missing information that needed to be added. Additionally, SynTerra followed AWIA and US EPA guidelines (Gay et al. 2018; US EPA 2019b) to ensure that each ERP was updated to the US EPA's standards. Information gained from workshops included updated internal and external contacts, system or asset standard operating instructions, communication plans, general and incident-specific response plans outlining detection methods, mitigation steps, and post-incident actions. This process created a useable ERP that could be pulled off the shelf or quickly accessed virtually on iPads and computers in an emergency. A few key takeaways (Figure 5) gained from working with the clients are as follows.

Key Takeaway 1: Maintain a Diverse Planning Team

Similarly to key takeaway 1 in the risk and resilience section, including personnel from all levels of the organization in the process is vital to developing an ERP. Engaging a diverse group allowed SynTerra to gather as much information as possible about how the utility currently responds to emergencies and how to improve the process. The people working directly with the assets have a better understanding on how to handle the asset if an emergency was to occur, and

people from upper management or public relations typically know how to respond and communicate with the public if an event was to occur. So, engaging a diverse planning team ensures that the plan is as thorough and useful as possible.

Key Takeaway 2: Use the RRA as Guidance

In general, the RRA determines the risk for a scenario that "could" happen, while the ERP addresses the actions for if something "does" happen. When updating the ERP of each utility, SynTerra used the information from the RRA to guide the ERP process. For example, if the RRA identified that the utility could not serve its clients without an asset such as membrane treatment technology, then SynTerra encouraged the development of an asset-specific response plan and procedures to quickly resume drinking water service to the customers. SynTerra encouraged the client to update the ERP with the results of the RRA in mind.

Key Takeaway 3: Regular Conduct Tabletop Exercises on Emergency Responses

A key element in successful emergency response is how well the staff is trained to react. If the staff is never trained on emergency response procedures and does not understand who to contact, how to repair the asset, or what to do when an event arises, then the situation could escalate to more severe consequences such as loss of service or loss of life. The ability to respond quickly and efficiently is crucial in any emergency situation; therefore, annually conducting ERP trainings and scenario-driven tabletop exercises can aid in a utility's resiliency.

Key Takeaway 4: Review the ERP after an Emergency Situation has Occurred

In addition to annually reviewing the ERP, the utility should also review it after a confirmed emergency situation occurs. This is recommended so that the utility can identify whether process improvement is required. This is a great way to go over lessons learned and to come up with ways to respond more efficiently if future events occur.

Key Takeaway 5: Actively Coordinate with the LEPC and Other Emergency Organizations

Utilities should have an ongoing relationship with the Local Emergency Planning Committee (LEPC) and other emergency organizations so that the response plan is always up to date. The LEPC can help identify and plan for emerging or continued threats, therefore improving the utility's resiliency.

Overall, a utility should have an updated ERP to increase resiliency and protect their customers. A general mission of most South Carolina water utilities is to provide safe and affordable drinking water to its customers. To fulfill that mission, a utility needs to not only understand its risk, but also

The Road to Resiliency for South Carolina Water Utilities



Figure 5. ERP key takeaways.

know how to quickly and efficiently respond to an emergency so that it can protect the health of its customers by providing a reliable supply of safe drinking water.

DISCUSSION

“The low-and-slow investment in getting staff members engaged in and trained on risk management might be more palatable relative to the potentially high financial, societal, reputational, environmental, or public health cost of an unexpected incident” (Setty et al. 2019). Communities in South Carolina are becoming more interested about the source and quality of their drinking water. With news headlines featuring drinking water contamination events to emerging threats such as Per- and polyfluoroalkyl substances (PFAS) and cyanobacteria blooms, source water pollution, and utility asset failures, it is important that utilities be resilient to current and future threats.

South Carolina utilities should use the AWWA J-100 standard as a guide for ongoing risk and resilience management. Each utility should establish a team that creates and expands a broad and diverse knowledge base and viewpoints in the utility to lead risk and resilience management. Each utility should calculate the URI as a resilience baseline and revisit the URI annually, as it provides a tangible metric for success. Establishing and maintaining an extensive asset management program provides multiple benefits for the utility in risk and resilience management. Including a priority evaluation in the program that identifies and prioritizes the critical assets provides for smart capital improvement and

other utility planning. Using the program to actively track maintenance and asset status also decreases potential vulnerabilities. Then, reviewing those vulnerabilities and assessing potential countermeasures annually allows the utility to protect critical assets and increase resilience. Finally, following the J-100 standard produces risk as a dollar amount, which means that risk-reduction measures and options can be evaluated using a cost-benefit analysis.

Ultimately, identifying the utility’s vulnerabilities and adjusting emergency response accordingly increases the South Carolina community’s drinking water quality and the utility’s overall resilience. Evaluating risk and resilience and implementing an ERP is not a one-size-fits-all approach. Tailoring responses and budgeting for a rainy-day fund should focus on the utility’s challenges and on the needs of its customers. Ensuring that the plan is put into action and that information gained from the exercise is incorporated into business solutions could be an important step to upholding the utility mission.

It’s long been known that the quality of human life can be directly related to the quality and quantity of water that sustains it (Levallois et al. 2019). Therefore, it is crucial for water utilities to change their mindset from being reactive to following a proactive approach that protects human health for generations to come. South Carolina is experiencing exponential growth; the last census numbers demonstrated that areas of the state encountered population growth by more than 10% for the fifth decade in a row (Census 2020). With new population comes new demands on South Carolina water resources, and water utilities are facing rapidly evol-

ing challenges related to that growth. While no one can predict every potential threat, scenario-driven planning bolsters preparedness for responding to unexpected occurrences and previously unknown threats. Therefore, it is beneficial for all South Carolina drinking water utilities to actively engage in the RRA and ERP processes. Planning and preparedness make for operational resiliency and a future of reliable and safe drinking water in South Carolina.

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“I Won’t Use the Term Dumbing It Down, but You Have to Take the Scientific Jargon Out”: A Qualitative Study of Environmental Health Partners’ Communication Practices and Needs

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Abstract. Effective research translation and science communication are necessary for successful implementation of water resources management initiatives. This entails active involvement of stakeholders through collaborative partnerships and knowledge-sharing practices. To follow up a recent study with the National Institute of Environmental Health Sciences (NIEHS)–funded Center for Oceans and Human Health and Climate Change Interactions (OHHC²I) project investigators, the center’s Community Engagement Core (CEC) documented center partners’ science communication practices and needs to inform a collaborative training and improve investigator-partner bidirectional communication. Thirteen (13) individuals participated in 10 semi-structured qualitative interviews focused on their research translation needs, science communication and dissemination tactics, and interactions and experiences with scientists. Based on our findings, we recommend a collaborative, scientist-stakeholder training to include plain language development, dissemination tactics, communication evaluation, stakeholder and intended audience engagement, and strategies for effective transdisciplinary partnerships. This work contributes to the knowledge and understanding of stakeholder engagement practices specifically focused on science communication that can enhance relationship-building between academia and partners involved in environmental health–focused initiatives in the context of South Carolina but applicable elsewhere.

INTRODUCTION

Bidirectional communication and active engagement with stakeholders is an increasingly common requirement for successful implementation of interventions in environmental health sciences, water resources management initiatives, and addressing complex environmental problems (Megdal et al. 2017; Paulson et al. 2017; Freeman et al. 2018; Reed et al. 2018; Mackenzie et al. 2019; Neet et al. 2019; Misra et al. 2020). The Community Engagement Core (CEC) of the National Institutes of Health (NIH) National Institute of Environmental Health Sciences (NIEHS) funded Center for Oceans and Human Health and Climate Change

Interactions (OHHC²I) at the University of South Carolina recently conducted a study with center investigators about their research translation and science communication practices and training needs (Altman et al. 2020). This paper describes a follow-up analysis of the center’s partners’ science communication practices and needs with the ultimate goal of ensuring clear and productive communication between investigators and their stakeholders. In addition, integrated water resource management will benefit from learning about partner preferences and successful practices for interacting with partners and translating scientific research into useful applications in the context of South Carolina. This work contributes to the knowledge and understanding

of stakeholder engagement practices specifically focused on communication that can enhance relationship-building between academia and partners involved in environmental health-focused initiatives.

There is an emerging trend to restructure research grant application and review processes, provide funding opportunities for research partnerships, and incorporate training and education resources for scientists and community members to ensure that communities are engaged in and benefit from health research (Jessani et al. 2018; Tait and Williamson 2019; Grayson et al. 2020). These cooperative initiatives provide an opportunity for historically excluded segments of the public that have been disenfranchised by the research enterprise to be actively engaged in addressing health inequities within their communities (Prochaska et al. 2014; Huang and London 2016; Neet et al. 2019). The NIEHS and the National Science Foundation (NSF) currently fund four research centers of Oceans and Human Health (OHH) across the United States. These OHH centers examine how human health may be affected by emerging environmental conditions of the Great Lakes, coastal waters, and oceans. The OHHC2I at the University of South Carolina is a collaborative partnership with the College of Charleston, the Citadel, Baylor University, and the University of Maryland Center for Environmental Science. The OHHC2I's specific foci include freshwater harmful algal blooms (HABs), infectious microbes (*Vibrio* spp.), and contaminants of emerging concern (microplastics). The goal of OHHC2I is to enhance knowledge of the potential effects of climate change on *Vibrio* bacterial infections and the production of toxins from freshwater cyanobacteria, both of which may adversely affect human health. The OHHC2I develops tools such as forecast models to inform the public about health risks associated with these organisms and with the occurrence of microplastic pollution in coastal waters. The center consists of four research projects with an administrative core and a community engagement core (CEC; ohh.sc.edu). The CEC helps ensure that research is appropriately translated and helps facilitate information flow between center investigators and center partners, which is an important component of the center. NIEHS defines research translation as the process of communicating and promoting the application of scientific accomplishments, and they developed a translational research paradigm to help researchers design research, identify partners and stakeholders that can use the research in environmental decision-making, and track progress (Pettibone et al. 2018).

OVERALL GOAL

This study aimed to better understand the science communication practices and needs of center stakeholders to improve collaboration between investigators and their key partners, with the ultimate goal of improving multilevel

science communication and research translation. The findings will assist with the development of collaborative trainings for investigators and their stakeholders, facilitated by the center's CEC team and key partners. In addition, results regarding stakeholder communication needs will provide the CEC with information on how to support and recommend dissemination strategies of key partners.

BACKGROUND AND RELATED WORK

The current literature on research translation and science communication-related interactions among researchers, stakeholders, and community members demonstrates that the process is evolving toward participatory approaches and knowledge co-production (Fleming et al. 2014; Winterbauer et al. 2016; Beier et al. 2017; Reed et al. 2018; Mackenzie et al. 2019). Collaborative partnerships between researchers and stakeholders can result in substantial environmental policies and social benefits (Brauer et al. 2004; Holmes and Savgård 2009; Freeman et al. 2018; Misra et al. 2020). Increased stakeholder involvement improves relationships and understanding between researchers and their intended audiences and serves as a critical capacity-building factor for environmental decision- and policy making (Holmes and Savgård 2009). In South Carolina, integrating stakeholder and public engagement with resource management planning has been instrumental in the development process of a state water plan. The management of water resources and related issues are local and should include a diverse group of stakeholders in various phases of the planning process (Walker et al. 2019). Some examples of successful OHHC2I community-focused collaborations in South Carolina include ongoing work with center partners at the Lake Wateree WaterWatch citizen-science group (<https://sites.google.com/site/watereewaterwatch/>), the Midlands Rivers Coalition (<https://howmyscriver.org/>), the Check My Beach collaboration (<https://www.checkmybeach.com/>), and collaborations with the Lowcountry Alliance for Model Communities (LAMC; <https://lamcnc.org/>). On a statewide scale, the center and its partners are working together to develop a holistic Community-Managed Disaster Risk Reduction (CMDRR) training that is being piloted with participants from environmental justice (EJ) communities around South Carolina (SC). Formally known as EJ STRONG, this collaboration's main activity is a community-level preparedness training for natural disasters such as hurricanes, floods, and wildfires. As part of the training, tools are presented to assist block captains from EJ communities with tasks they will conduct within their communities to enhance community-based disaster preparedness.

Community and stakeholder engagement is a fundamental practice in environmental health sciences to promote public health, and bidirectional communication

between researchers, community members, and stakeholders increases the potential to promote public health initiatives and preventive behaviors from conditions that impact human health and well-being (Friedman et al. 2015). However, multilevel stakeholder involvement, discussion, and collaborative resolution of critical environmental health issues are often lacking. While community-engaged research can help improve community resilience (Burwell-Naney et al. 2019), lack of involvement and representation in decision-making may result in additional environmental burdens on community segments—particularly minority communities, which are already cumulatively burdened by higher environmental health risks (Prochaska et al. 2014). Stakeholder participation can also be obstructed by deficient transparency, inadequate communication of scientific knowledge, stakeholder inability to interpret research findings, and limited capability of policy makers to incorporate scientific results into effective environmental decisions and policies (Holmes and Savgård 2009).

Science communication is the process of providing information that assists an intended audience in making sound decisions and understanding the impacts associated with their decisions (Fischhoff 2013). Communicating research objectives and findings with the community directly affected by the results enhances their participation in future research projects (Brauer et al. 2004; Mackenzie et al. 2019). Disparities in environmental literacy (McBride et al. 2013) and environmental health literacy (White et al. 2014; Finn and O'Fallon 2017; Gray 2018) may influence public advocacy and understanding of environmental issues (Friedman et al. 2015). Engaged research and other initiatives related to boundary spanning and knowledge co-production produce knowledge that is more meaningful for the participants (Mach et al. 2020). In this regard, boundary-spanning organizations help with information dissemination and uptake and help perform key functions that distinguish their work from others (Gustafsson and Lidskog 2018). In addition to the OHHC2I's CEC functions, some examples of such successful organizations in the United States are the National Oceanic and Atmospheric Administration's Regional Integrated Science and Assessments program (<https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/RISA/About-RISA>), the National Estuarine Research Reserve System (<https://coast.noaa.gov/nerrs/>), and others. Individuals employed by such programs and organizations perform key boundary-spanning functions that include facilitation, strategic planning, and project management (Goodrich et al. 2020).

METHODS

This study used purposive (intentional selection of interviewees with strong topical knowledge) and snowball

(participants identified additional interviewees) sampling (Patton, 2002) to invite OHHC2I partners to participate in qualitative interviews. The research team contacted center investigators to request recommendations for key center partners to serve as interviewees, who were then invited via email to participate in virtual qualitative interviews. Twenty-two (22) individuals were contacted on August 5, 2020, and 13 individuals participated in 10 interviews between August 13 and October 1, 2020. One group interview included 3 interviewees; all other interviews only had 1. Informed consent was obtained from all interviewees. Semi-structured qualitative interviews focused on stakeholders' science communication and dissemination strategies and research translation needs. This research was approved by the University of South Carolina Institutional Review Board.

The CEC team created an interview guide, which went through several rounds of revisions. The final version of the interview guide consisted of 24 open-ended questions (see Appendix A). The questions probed for stakeholders' organizational foci, intended audiences, dissemination tactics, science communication needs and preferences, how they communicate uncertainty, and their interests in research-translation training. Each interview lasted 45 to 60 minutes and was facilitated in pairs (one facilitator and one note-taker) by five authors. All interviews were conducted virtually using videoconferencing software, Zoom (zoom.us, 2020), due to in-person meeting limitations during the COVID-19 pandemic. Interviews were audio recorded and transcribed verbatim by a professional transcription service. Original interview audio files were uploaded securely to a password-protected folder with limited user access. Transcripts were reviewed for accuracy by three authors and were uploaded in NVivo 12 (NVivo, 2019), a qualitative data analysis software, for thematic coding.

Data analysis involved a semantic (explicit, as stated) thematic approach (Braun and Clarke 2006, 2019). The authors utilized a hybrid approach to thematic analysis, using both deductive and inductive coding (Fereday and Muir-Cochrane 2006) for a more complete analysis of collected qualitative data. The first iteration of the codebook was deductively developed based on the interview guide by four authors with qualitative data analysis experience. Three authors initially coded two interviews each using the first iteration of the codebook and organized the data into NVivo 12, then analyzed two transcripts to refine the codebook inductively before testing for consistency in coding. Intercoder reliability demonstrated agreement above 95% between the three coders, and 100% coding reliability was achieved after review and discussion between coders in NVivo 12. Coders communicated frequently by phone and email to discuss discrepancies in coding to maintain consensus in coding themes. As new themes emerged from the data during coding, they were added to the codebook, which the

coders continued to refine for consistency using an iterative process (Laditka et al. 2009). Notes taken during interviews were consulted alongside the transcript during the coding and analysis stage, and original notetakers and facilitators were granted review of compiled themes and analyses to ensure full team agreement.

RESULTS

Interviewees' organizations can be categorized as nongovernmental organizations (four), state or federal regulatory agencies (four), water utilities (one), and a water resources research center (one). All interviewees have a mid-to high level of seniority in their organizations. Their work includes water-quality monitoring, meaningful engagement of environmental justice communities, conducting environmental research and populating databases, and supporting and making regulatory decisions or policy recommendations. Organizations' priorities included providing ongoing education, communicating data, and sharing resources to aid decision-making in topics connected to the protection of public health and the environment. When asked to describe the interviewees' environmental health foci and interests related to OHHC2I research, interviewees predominantly mentioned harmful algal blooms and *Vibrio* bacteria. Interviewees also mentioned environmental health topics such as contaminants of emerging concern and unregulated contaminants (microplastics), reproductive health, air quality, environmental justice, and infrastructure needs (e.g., weatherization of homes).

The main themes from the interviews presented in this section include: (1) communication practices, (2) communication challenges, (3) perceptions of research translation, (4) communicating about uncertainty, (5) collaboration with scientists, and (6) training in science communication and research translation. Main themes and subthemes can be found in Table 1, and the full table of results is available in Appendix A.

COMMUNICATION PRACTICES

When asked about the organizations' intended audiences for environmental health communication, interviewees mentioned scientists and academia; policy makers (including congressional outreach and local politicians); water professionals, including large and small utilities in the state; physicians; the general public; government organizations (federal, state, tribal, and local government); and NGOs. Specialty populations mentioned by some interviewees included certain community residents or homeowners' associations, youth, environmental justice groups, African American community members, guidance counselors and members of the education system, and specialty-interest groups. When asked how they define *community* as it pertains to their work, several interviewees defined their community as a geographical location and its residents, while others defined it as the different populations and subpopulations with whom the interviewees work. For others, the community was described as those that utilize the informational resources (e.g., reports, tools, forecasts, advisories, publications, databases) and natural resources

Table 1. Summary of Emergent Themes

Main Themes	Subthemes	Interview Question(s) through which Themes Emerged
Communication Practices	Intended Audiences, Definition of Community, Communication Channels, Dissemination Partners, Ongoing Dialogue, Measures of Communication Effectiveness	5, 6, 7, 9, 10, 11, 17
Communication Challenges	Impact of COVID-19 on Communication, Technology, Building Relationships, Mistrust, Working with Public, Better and More Timely Communication between Entities, Working with Others, Time Constraints	8
Perceptions of Research Translation	Perceptions of Research Translation	12
Communicating about Uncertainty	Experiences with Scientists, Comfort Level with Intended Audiences	19, 20
Collaboration with Scientists	Science Data Sources, Working with Scientists, Providing Information Needs to Researchers, Ongoing Dialogue, Timing of Results Dissemination, Preference for Receiving Research Finding	13, 14, 15, 16, 21, 22
Training in Science Communication and Research Translation	Past Training, Training Needs, Science Communication Needs	18, 23, 24

A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

(e.g., drinking water, lake/reservoir, shellfish harvesting areas, swimming beaches) facilitated by the interviewee.

Interviewees reported multiple communication methods to engage with their intended audiences. The most commonly mentioned were websites, social media, flyers, newspaper articles, in-person communication, and emails. In-person communication channels involved meetings (e.g., community and public meetings, two-day events), one-on-one contact with community representatives or a public participation coordinator, phone calls or an open line to the public via telephone for questions, utility plant or community tours and career days, festivals, and participatory learning and action (PLA) tools like focus groups and charrettes. Other communication channels mentioned include video-conferencing platforms, blogs, radio, reports, videos, press releases, television, and conferences. One interviewee indicated relying on printed advisory signs at points-of-access of recreational waters. Interviewees also reported they often communicate with their audiences through printed communication via peer-reviewed literature, newsletters, academic press, or organization journals. A table with exemplary quotes can be found in Appendix B.

Interviewees also mentioned partnering with multiple academic, federal, state, and professional organizations to disseminate environmental health information, and they stressed the importance of such partnerships. Partners helped each other not only with information dissemination, but also with addressing ongoing and emerging issues of concern, crafting messages, and facilitating community involvement in projects. Many interviewees practiced an ongoing dialogue with their intended audiences. They reported responding to questions and data requests from contractors and members of the public, as well as in in-person meetings and individual interactions through emails and phone calls or at conferences. As federal agencies have legal requirements for stakeholder dialogues, interviewees reported that interested audiences often reach out to them directly.

The majority of interviewees reported that their organizations assessed the effectiveness of their communications efforts and indicated areas for improvement in conducting evaluations. Evaluation strategies mentioned include organizational retreats, online evaluations, follow-up surveys, attendance counts, and other forms of feedback from community members. Some organizations had dedicated units or personnel to perform communication and outreach, along with evaluation of these activities; organizations that did not have a designated person reported having difficulties with performing such evaluations.

COMMUNICATION CHALLENGES

Interviewees identified several challenges with reaching their intended audiences, specifically in engaging certain population segments within the general public. One

interviewee identified a challenge in reaching diverse audiences that have not traditionally participated in research, despite attempts to directly engage these community members in locally preferred settings. Another interviewee indicated that funding constraints made it difficult to distribute information to their intended audiences.

Interviewees emphasized the challenge of establishing trust and credibility with their audience (e.g., public, policy makers) to create sustainable partnerships and relationships. Several of the interviewees represented a regulatory agency; for those interviewees, an immediate barrier they worked to overcome is public suspicion and distrust of the government. One interviewee described such public perception and how the agency overcomes it:

Being a large state agency, we have to overcome that stereotype that, you know, "we are the government." There is a lot of mistrust you have right off the bat when coming in and trying to help a community, if you're a government agency. I live in this community, [where] I work, you know, I have relationships with them. So that's always, to me, the first hurdle you overcome is establishing that trust, and getting them to see past the large state agency, and what we're there to do. . . . And then our public participation coordinator [builds] these very strong relationships with [some] of the community leaders or the key community [members] of these groups that we're working with, and they give some pretty honest feedback and we always learn from that, too. (Interviewee 3)

Interviewees have attempted to mitigate these barriers by building relationships with various communities, creating and training block captains or citizen academies to reach audiences in a peer-to-peer format and by using bidirectional communication methods on an ongoing basis to ensure that activities were understood by, supported by, and reported back to the community.

The community will identify the individual that will serve as—we're calling them block captains—so they were really responsible, let's say, for a street or maybe a street or two in their neighborhood, and they will be the ones that will have robust conversations with their people on their assigned street or streets. And [name of the organization] is the one that will have the direct communication with that individual. We will provide training to them so that they are trained on emergency planning, preparedness, recovery, and also some other training in leadership development and some other things that we find that has been useful for someone that would be a key communication person in a community setting like that. (Interviewee 1)

Interviewees also identified many challenges around the use of technology to communicate with their intended audiences, including (1) lack of access to digital devices or

a reliable internet source, (2) internal constraints on use of social media as an official entity, and (3) limited personnel/time to devote to social media and/or website creation and maintenance. This was made more challenging at the onset of the novel coronavirus, SARS-CoV-2 (COVID-19), pandemic when previously successful and preferred in-person communication methods became virtual. Interviewees' organizations adopted videoconferencing platforms with mixed success, but they had to cancel annual meetings, experienced difficulty facilitating meaningful conversations in an online format, and found that intended audiences were either unfamiliar with or unable to access these platforms. In response, one interviewee found success in utilizing peer assistance to connect audience members to virtual meetings over the phone.

But all of those opportunities for citizens' gathering, citizens' meetings have gone out the window. And so, we have done a few surveys trying to follow up with a couple of communities that are trying to—they just want to know what's going on. But that's been the most difficult part, is the interaction with the individuals, and particularly the groups of individuals that share common concerns. You can do a virtual meeting, but with a lot of private citizens trying to do Zoom and Skype and things like that are unfamiliar to them. And it's not a comfortable media for a back-and-forth exchange when only one person at a time can speak. So, to me right now the pandemic is the biggest impediment to interaction with our audience. (Interviewee 4)

Another interviewee found that offering virtual content increased their reach and reduced costs.

Our whole model of doing things is based on getting people together in groups and providing in-person training. And so when that became impossible to do we had to switch gears totally to go to virtual content. So that's been a challenge, but it's also been very rewarding in certain ways, because now we're actually able to reach more people. So we've seen an increase in the number of persons that have signed up for some of our workshops and events because it is much easier for them to be able to spend a couple of hours logging on to a webinar, versus [traveling]. And so saving the time and expense and being able to get our content virtually has turned out to be in some ways a positive thing. (Interviewee 8)

PERCEPTIONS OF RESEARCH TRANSLATION

Interviewees defined research translation as (1) the process of communicating science or research findings to their intended audience in a way the key audiences can understand, or (2) the process of applying research to support policy development or actionable steps. One interviewee defined

research translation more specifically as framing a message from the perspective and mission of the organization.

The process of science communication to an intended audience was described as a function of increasing awareness about an issue and improving public decision-making. Various factors were listed, including audience identification, making the content relevant, and using the appropriate vernacular or level of detail to ensure understanding. Interviewees included the need to present technical information in plain language and in a format (e.g., graphics, reports, pamphlets) that allowed their intended audiences to quickly and easily understand research findings or scientific messages. Two interviewees shared that they translated research to their intended audiences through nested messages of increasing degrees of technical complexity, allowing consumers of different levels of understanding to dig into the weeds of the analyzed and synthesized data.

Being able to translate [the research] to [the] citizenry, and then being able to translate risk to citizenry in plain language. That the message is plain, clear, gives the risks in a—yeah, basically in a very plain language, and maybe even associative to language . . . short, succinct, kind of study, scope, direct impact. And then supporting documentation for further digestion [to] dig into the weeds of it as well. (Interviewee 9)

One interviewee reflected on how feedback helped shape and improve their communication effectiveness:

[What] we found out is that the way that we were communicating was going over people's heads. So we changed the language and we have gotten more refined with how we share information, the language that we use, the mechanisms which we share that information . . . so we were using language that they were not familiar with, we were using acronyms, you know, the typical things that you do when you are working in a field of science and technology. We had to break that [down] and be able to communicate with our communities in a language that they could understand. So we provide [an] infographic and then there are further links that go to the abstract, and then there's a further link that provides them the full report. (Interviewee 1)

Some interviewees cautioned that translation of research to plain language should not assume that the average layperson is unintelligent, but that it was important to provide information that is digestible by the general public with varying levels of familiarity with scientific terms and concepts and varying perspectives.

I've been to meetings where scientists are trying to explain what they do, you know, and the general public is pretty intelligent. You get people who are artists and people like

A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

that and they wanna learn, but if you start—if you talk to them in language they don't understand, it's ridiculous. So we need to do better at that. . . . You [want to] disseminate in language that the public understands through blogs and journals and this and that to the public about what [the science] means. And I've found that's sort of an art—how to take the scientific literature and translate it into an intelligent layman's point of view. (Interviewee 2)

One interviewee disagreed on the need to translate research when scientists are the intended audience, while most assumed that scientists can grasp others' research.

And that's not easy because we think in very abstract terms, we have languages that are very—and even within science, you know, you talk to somebody else in another field and you say, wait a minute, what are you talking about? (Interviewee 2)

I prefer talking with scientists just 'cause even if you're in completely different scientific disciplines, there usually is enough overlap in [educational] backgrounds that you can actually talk with each other about very technical topics and [ask] very relevant questions. (Interviewee 10)

From the interviewees' perspective, the process of applying research was the responsibility of the scientist/researcher, and the public/community was considered the recipient of such packaged applications. According to interviewees, this process entailed identifying the impacts of the research findings on a specific audience or on the general public and developing recommendations for policies, prevention targets, or mitigation steps to protect public health. One interviewee commented on how the translation process can be lengthy, and the lack of appreciation of science can be attributed to the public's lack of knowledge of how the scientific process works.

Maybe 20 years from the ideas that come out of a basic lab to its ability to actually impact patient care. That was the tradition of translation, but then I think translation is also the job we have of educating the general public about science, and that's difficult because there seems to be in this country a lack of understanding and appreciation of science. . . . I think the biggest problem we have in "translating" scientific ideas to the general public is people have no idea how science works. I mean, science is a process. (Interviewee 2)

COMMUNICATING ABOUT UNCERTAINTY

When asked, "How comfortable do you feel communicating with your intended audiences about uncertain research findings?" all interviewees reported that they were very comfortable. Their comfort in receiving communication

from scientists on conditional results was attributed to their understanding of the scientific process and the communication skills of the scientists relaying the information. Regardless of their role in receiving or presenting uncertain findings, interviewees agreed that because science is always evolving, uncertainty is understood as a part of the scientific process. Thus, there was comfort in discussing research findings before peer review. In a similar vein, interviewees discussed the importance of presenting novel, contradictory, and unexpected findings, noting that they add to the literature and inform future studies and research applications.

An interviewee operating as an official entity of its state government, however, described the delicacy of presenting novel findings that are not well studied to other scientists looking for authoritative guidance on an issue that was not yet well understood.

So I have to be very careful in crafting these statements to those, and making sure researchers understand the curb and gutter especially that I have to play in, or our agency has to play in in that we can make definitive statements, and then we have to make sometimes educational statements that don't make it too definitive. And so we have to be very careful that we don't oversell—we don't want to make statements that we have to roll backwards. . . . Research has a lot of eyes on them. (Interviewee 9)

Interviewees quickly differentiated between the scientific community and other audiences regarding their comfort around communicating uncertainty. Several interviewees reported feeling very comfortable communicating uncertain findings to their intended audiences, and a few felt that it is necessary to do so in order to protect public health or improve decision-making. However, the majority of interviewees attributed absolute thinking to the general public, which impacted their level of comfort in communicating uncertain findings to audiences that demand firm answers. Some believed this was due to a lack of public understanding of the scientific process in general, while others pointed to the public's need for clear guidance to make decisions for their health and safety.

So, we don't have, for instance, a water quality index where we can take all of our data and parameters and roll that up into a "What's the state of the lake?" and "Is it getting better or is it getting worse?" So, there are things you can point to, but the information is not really well collated or indexed into a measure that you can just say, "Here's the number for right now and here's the trend over time." That would be extremely helpful to be able to do that. . . . When you get to the broader community, [people are] less interested in the hard science and they just want to know, "Is the water safe to swim in? Are the fish healthy? How's that changing and what are the trends?" (Interviewee 5)

Right, that's always difficult because the general public wants to have an answer, with no uncertainties. And in science, you just can't. (Interviewee 7)

When describing communication about uncertain risk levels to an intended audience, the level of comfort significantly decreased.

Trying to explain [harmful algal bloom] and put the risk in a way that a layperson can understand and accept can be the some of the biggest challenges I've encountered over the years. (Interviewee 3)

Interviewees responsible for providing statements or warnings about water quality and harms to public health reported needing to balance the public's need for information to make sound decisions while limiting their misinterpretation of risks. These interviewees also discussed the importance of tone so as not to raise alarm while also not downplaying a potential risk to the point of it being ignored.

So, I think that translation from science and engineering to a lay audience trying to give them some level of comfort and true understanding but not overwhelming them or making them more nervous is a challenge I think with anybody. (Interviewee 10)

COLLABORATION WITH SCIENTISTS

Interviewees' relationships with scientists and the needs of their intended audiences dictated their preferences for working with scientists at the beginning of a research project, as well as the timing and format for receiving research dissemination products. When asked where interviewees acquire environmental health data, many interviewees reported generating their own data in addition to using secondary data sources. Secondary sources included federal and state government (e.g., Centers for Disease Control and Prevention, United States Environmental Protection Agency, South Carolina Department of Health and Environmental Control), scientific-based sources (e.g., academia, scientific literature, scientific community), and partnerships (e.g., riverkeepers, utilities, and municipalities to collect data, and partner organizations involved in research).

Interviewees indicated that they have good experiences working with scientists and make progress through communication with scientists. Scientists offered technical expertise and helped interviewees meet the needs of the community, and such collaborations helped translate findings into something more meaningful on a bigger scale. Successes in these experiences were attributed to mutual agreements on the work process (e.g., collaborative problem-solving model and community-based participatory model), close working relationships, and having a cohort of collaborators. Oftentimes collaborations took a long time to establish and maintain, but

such relationships built trust and made collaborations more enjoyable.

I have a large cohort of collaborators that I work with. Most of the environmental problems that are out there right now are very multidisciplinary, so you have to have a cohort of specialists. The best thing you can do as a scientist is actually know where your knowledge starts and stops. The worst thing you can do is actually think that you can do more than what you really can do. So, to fill those gaps in, you find people to work with; collaborators. (Interviewee 7)

We love partnering with other organizations. We're a relatively small nonprofit organization, so partnering is very helpful. . . . And so we really enjoy being at the table and providing input for our members. (Interviewee 8)

Interviewees were asked to describe their experiences in providing information needs to researchers at the beginning of a project; their responses varied from "not being involved in research" to "requests for information occur all the time." A description of information needs that interviewees provided to researchers included contacting and communicating with collaborators' networks, providing data to scientists, supporting trainees with their projects, and providing letters of support for grant proposals. Most interviewees agreed there is encouragement from researchers for ongoing dialogue, which aided the receipt of timely information.

I try to run our center as a collaborative center. And I'm always trying to be open to forming teams of people to work on projects. I've just found from my professional experience that always works better than trying to go out by yourself, design your own project, get your own students, stay in your own little spot, and then send the information out to others. I think it's less productive than kind of collaborating on the front end and getting information from people on the front end. (Interviewee 6)

Interviewees conveyed a preference for receiving data and information from other scientists and researchers on a consistent basis, as well as allotting a set time period to distribute and communicate the information to available formats (e.g., publications, website, mobile applications). Many interviewees indicated that such information came from personal networks of established connections with scientists, reaching out to colleagues, and other sources of scientific communication (e.g., presentations and publications). One interviewee described seeking collateral information to help guide decisions, but they ultimately stated that formal decisions cannot be made on uncertain findings due to their impact on the general public.

Some interviewees expressed concerns of constraints on the information flows from the academic community, which

is inherently guided by the peer-review publication process. They noted that the publication process can take too long to wait for release of research results to the public after they are published. Close relationships between scientists and certain interviewees, however, put new research findings on the radar of regulatory and other decision-making authorities before the results were distributed through academic channels.

The ones that I know personally are happy to talk to me about what they're seeing, what they think their research is showing and telling them. And then [they] slap the cuffs on and say, "you can't share this with anybody until I get it published." . . . That doesn't necessarily stop us from continuing to work together and build on those. . . . So there is a built-in screen, a built-in blockade between the research community and the policy makers. (Interviewee 4)

Interviewees concurred that the urgency of receiving research results depended on the severity and risk or threat to human health and/or the environment. They preferred to be informed on research progress when scientists were confident in their results and if the results indicated any potential risks to the general public. For example, information with immediate impacts on human health or the environment should be conveyed as soon as possible, as opposed to distributed after publication. In particular, interviewees working in regulatory agencies preferred to receive findings in time to develop health risk communication messages along with developing policies and regulations (if applicable) to protect the public and the environment. All interviewees agreed that research should be made available to the public and that many audiences would benefit from more regular updates to inform health decision-making.

It depends on the speed with which that message needs to get to someone. For specific short-term advisories, making sure you're hitting the person that's at the location that may be directly involved in that [activity], and may need to know for their immediate needs. (Interviewee 9)

Interviewees indicated a preference in receiving research findings in concise, predigested options, like a one-pager or social media-friendly message, and as a full report or a peer-reviewed article. Some interviewees preferred to receive nested layers of detail in order to present these findings to the public in varying levels of complexity.

TRAINING IN RESEARCH TRANSLATION AND SCIENCE COMMUNICATION

More than half of the interviewees reported having had some training in research translation or science communication (e.g., short courses, seminars, workshops, webinars). However, there was variation in what interviewees considered formal training. A few interviewees defined formal training as college-level coursework, and there was some conversation

about how that was lacking in the scientific disciplines. While a few had taken a college-level scientific writing course, none reported any college training in research translation. Half of the interviewees reported that their training in research translation came from experiences on the job or in learning from other scientists and researchers. This included learning more about communities' needs or communication preferences, learning from mistakes, and piloting messages with a test audience.

I have no formal training. It's just simply I listen to our internal folks, and I do my best to translate it out. . . . I just literally learned on the job. That's my personal experience with it. . . . But, truly, if we're going to present anything to anybody we practice first, and we try and get a large audience who can provide different perspectives to make sure what we're saying is presentable. (Interviewee 10)

When asked about their science communication training needs, many interviewees mused that they were at the end of their careers or far enough into their careers that they felt sufficiently experienced. A few interviewees, however, identified training in plain language communication as a need.

So a big thing that has driven me in my career is trying to make sure that politicians and decision-makers understand science. . . . And so in order to do that—and again, I won't use the term dumbing it down, but you have to take the scientific jargon out. You have to take the heavy-duty statistics out of things and give politicians information they can understand to make decisions. And so I tell that to young researchers all the time. Because the young researchers, they'll understand the science. They're smart. They're smart as heck. They understand the science. They understand the statistics. But what they don't understand is how to explain that to a layperson. (Interviewee 6)

Other interviewees mentioned community engagement strategies when transitioning from in-person methods to others, developing training platforms, developing a system of alerts for findings of concern, helping with information overload, utilizing new tools that may assist in targeting the proper audience, and finding a way to measure those things effectively.

What are our science communication needs? It's always just the tools. The way to take maybe technical information and have it translated so it's easy to understand [given] the words we use. I mean, I always think it's great when you have the examples you can give. Also, if there's a lot being done with, you know, symbols and pictures, and [they] translate really well when they're done right. And then with our diversity in our communities, it's always working

to have it translated in different languages so it can be shared throughout our community. (Interviewee 3)

Interviewees also identified training needs in fundraising, project evaluation, media and digital presentation software, and best management practices. Some interviewees mentioned a need to find ways to better disseminate information and to improve engagement with specific, hard-to-reach audiences.

DISCUSSION

Findings from this qualitative study will contribute improved strategies for clear and productive communication between center investigators and center partners to facilitate effective research translation and science communication (see Figure 1 for partners' communication challenges and proposed solutions). Interviewees described their communication practices and related challenges, research translation approaches, uncertainty communication, collaborative relationships with scientists (e.g., center investigators), and research translation and science communication training experiences and needs. Interviewees worked for diverse organizations in environmental health and related sectors. Many of the interviewees worked in the water resources and public health sectors in South Carolina, and, not surprisingly, harmful algal blooms was named the highest-referenced focus area of the OHHC²'s research, which is an increasing issue of concern for both freshwater and marine environments with climate change (Ho et al. 2019; Gobler 2020). While many interviewees reported current partnerships with center investigators and water managers on issues related to HABs, this finding suggests a focus area for collaboration to ensure safety of potentially affected populations. Another commonly mentioned focus area was *Vibrio* bacteria. As *Vibrio* bacteria cause wound infections and seafood safety concerns that are predicted to increase in abundance with warmer temperatures and increased salinity (Deeb et al. 2018), improved collaboration with center investigators on these issues is critical to prevent and mitigate impacts to South Carolina coastal residents, tourists and recreational water users, the aquaculture industry, and seafood consumers. This is particularly important for communities that financially and culturally rely on seafood consumption and harvesting (Ellis et al. 2014; Friedman et al. 2015; Neet et al. 2019) and/or those that are overburdened by additional environmental exposures that increase adverse health outcomes (Prochaska et al. 2014; Wilson et al. 2017). Other focus areas mentioned, including contaminants of emerging concern (e.g., microplastics), reproductive health, air quality, resilient infrastructure, and environmental justice, are also currently represented in a variety of partnerships

with center investigators from an interdisciplinary approach as they relate to water quality and public health.

The wide range of intended audiences mentioned by interviewees indicates a need for increased bidirectional dialogue between scientists and partners regarding preferences and information needs early in the research process (Iwamoto et al. 2019; Mackenzie et al. 2019; Norström et al. 2020), as well as, potentially, investigator and partner training in audience segmentation (Prochaska et al. 2014). Tailoring research targets, applications, and packaging with intended audiences in mind can enhance the receipt of information by the end user, inform early decision-making, and ensure relevance (Beier et al. 2017; Iwamoto et al. 2019; Mackenzie et al. 2019; Norström et al. 2020). As interviewees agreed that an ongoing dialogue with their intended audiences is preferred and necessary for public health and safety, the availability of audience-relevant research at various time points in the research process can improve the flow of ongoing or time-sensitive science communication from scientist to community member (Iwamoto et al. 2019).

Interviewees reported both translating research into plain language for their audiences and developing recommendations for environmental and public health policies and prevention and mitigation measures. Specific communication tactics employed by interviewees also varied widely, which demonstrates the need for scientists to provide information to partners in various, often nested levels of complexity so it can be presented in multiple formats (e.g., pamphlets, emails, newsletters) and adapted for presentations at in-person and virtual events, meetings, or trainings, and include links to published results or online communication (e.g., publications or reports, databases, websites, social media pages, etc.). Given the impacts of COVID-19 on in-person meetings, small gatherings, and larger events, many interviewees adapted their methods of communication to online platforms, and many acknowledged some resulting technological barriers, particularly with populations that have limited access to and/or knowledge of internet applications (Atske and Perrin, 2021). Stakeholders with barriers to virtual communication thus may get left out of the research and decision-making process. While virtual communication can improve access where transportation, time, or physical ability may prevent engagement, organizations should implement multiple modes of virtual participation to ensure access for all. As interviewees listed a variety of dissemination partnerships deemed beneficial for tackling ongoing and emerging issues of concern, crafting messages, and facilitating community involvement in projects, similar partnerships should be encouraged or enhanced between partners and center investigators to improve information flows and/or increase their reach (Fleming et al. 2014; Reed and Abernethy 2018; Mackenzie et al. 2019; Neet et al. 2019).

Fischhoff (2013) identifies the evaluation of communication adequacy as an important part of science communication, stating it must (1) contain the information recipients need, (2) in places they can access, and (3) in a form they can comprehend. Interviewees reported performing evaluations of their communication as a beneficial but resource-depleting task. Some interviewees outsourced evaluations to third-party experts and modified their communication tactics based on the feedback (e.g., plain language, nested levels of information). Interviewees without dedicated personnel or resources for those tasks reported challenges in keeping up with evaluation measures for communication activities. Thus, there is an increasing need to add an evaluation component into research grants and budgets. The NIEHS OHH established a dedicated unit, the CEC, that performs such functions for center investigators and can help facilitate internal and external information flow, provide input into the development of messaging and evaluation plans, improve grantsmanship, and implement collaborative trainings on communication tactics for both investigators and partners. While the CEC supports this function for the center through training, technical assistance, and sharing of resources with center partners, moving forward it will be important for the CEC to collaborate with partners to help them identify their own funding sources for these activities, which will be critical for sustainability purposes.

Most participants agreed that scientists both understand uncertainty and do not typically require research translation when communicating about scientific concepts with other scientists. Thus, the targets of their plain language communication and careful messaging about contingent results or risks included the general public and specific subpopulations, which is consistent with other research (Bullock et al. 2019). One interviewee noted the nuances in jargon between scientific fields, however, which was in direct contradiction to another interviewee's opinion that educational training in the sciences enables understanding and communication with others outside a particular discipline. Boundary spanning, and education in this emerging discipline in particular, can facilitate enhanced communication between scientific disciplines (Goodrich et al. 2020). Two challenges the majority of interviewees encountered with their intended audiences were "black-and-white thinking" and what was perceived as a lack of general understanding of the scientific process. This aligns with other findings demonstrating a limited and conditional tolerance for scientific uncertainty from the general public (Gustafson and Rice 2020). Together, these findings suggest that training is warranted in framing uncertainty (Gustafson and Rice 2020), improving public understanding of science through community-engaged research practices (Wallerstein et al. 2020), and improving clear, layered science communication (Fischhoff 2019).

Working relationships with scientists were described by interviewees as mostly positive and highly beneficial when successful. Mutual agreements on the work process (e.g., collaborative problem-solving, community-based participatory research) and trusted, longstanding relationships with scientists were attributed to effective collaboration. Interviewees often built cohorts of scientific partners to meet their information needs and solve interdisciplinary problems. As interviewees identified a range of secondary data sources, these relationships were important for the timely exchange of research needs and emergent findings in order to make decisions and inform their intended audiences of potential risks. Suggested improvements in the information flow from scientist to stakeholder included increased consistency of communication and mitigation of constraints with investigators due to the lengthy publication peer-review process. These findings are consistent with published recommendations for greater interaction between scientists and decision-makers (Bolson et al. 2013, Bracken et al. 2015). As studies have documented the successes and challenges of transdisciplinary environmental partnerships (Huang and London 2016; Reed and Abernethy 2018; Mackenzie et al. 2019; Daniels et al. 2020; Misra et al. 2020), it is important that perceptions of successful factors in relationship-building, sustainability, and information flow be documented and compared for partners in various roles (scientist-investigators, scientist-stakeholders, community partners, etc.) to develop a model for best practices.

Formal training in research translation and science communication among interviewees was lacking, especially at the college level. Mirroring our findings from the investigator perspective (Altman et al. 2020), interviewees identified training in plain language communication as a priority need. Additional training was requested in project evaluation, media and digital presentation software, communication best practices, dissemination tactics, and engagement with hard-to-reach audiences. Interviewees, however, have amassed a wealth of on-the-job experience that can improve center investigator understanding of real-world applications of their research, and investigators can benefit from learning partners' perspectives, therefore promoting mutual learning and increasing understanding for successful implementation of innovations. This presents a unique opportunity for the CEC to facilitate a collaborative training to fill these gaps and increase investigator-partner knowledge-sharing.

LIMITATIONS

Limitations to this study included a small sample size (n=13) and limited categories of stakeholder organization areas of focus and intended audiences. Due to the nature of the study, OHH2I investigators named center partners for the interviews. These partners have established relationships with center investigators that sometimes span several

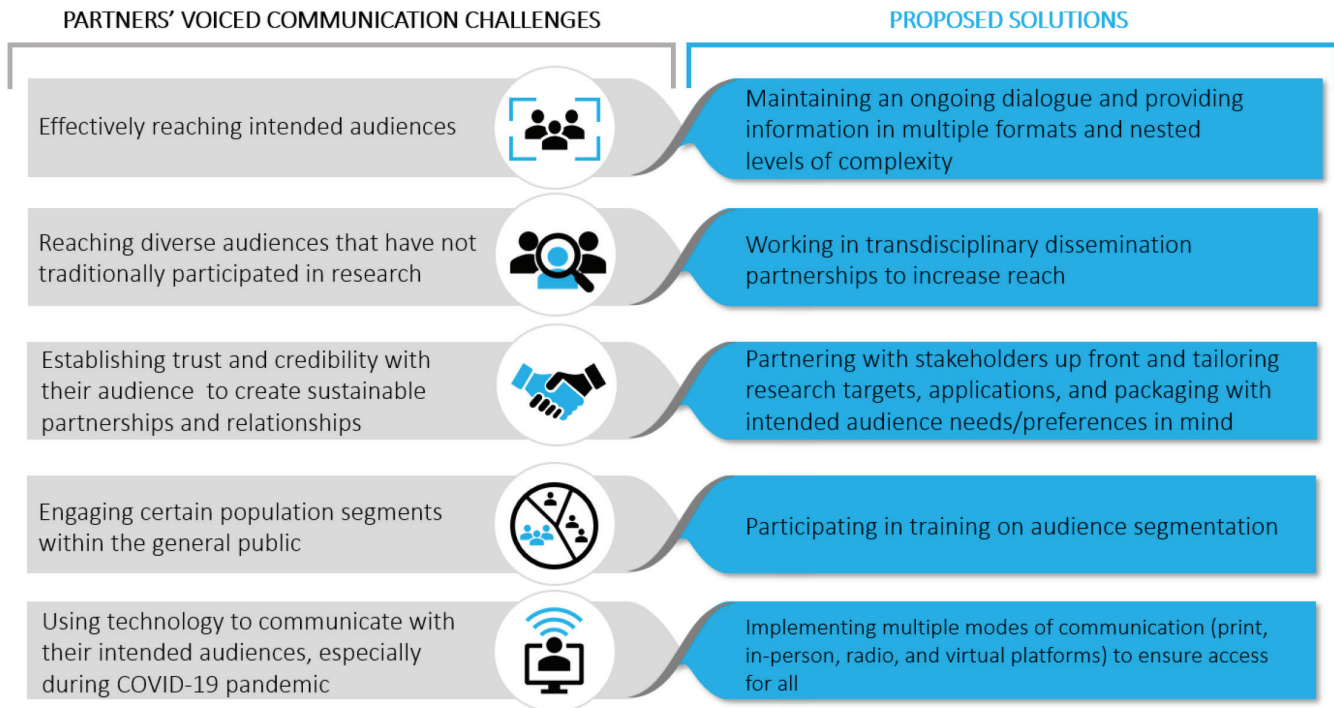


Figure 1. Partners' voiced communication challenges and proposed solutions.

decades. Many of the center partners, like the center investigators, represent an older demographic. Only a few younger professionals were interviewed for the study (those selected by a snowball sample). This represents a potential limitation for data source triangulation. In addition, the majority of the interviewees' work is geographically bound within South Carolina; these results may differ for a larger geographically dispersed and diverse stakeholder sample. As in other geographically restricted studies with small sample sizes (Bergeron et al. 2018), research with a broader and more diverse audience across disciplines, geographies, and subpopulations is warranted. However, recommendations regarding stakeholder engagement and trainings presented in this study may be applicable to other transdisciplinary partnerships.

CONCLUSIONS AND RECOMMENDATIONS

Trainings in a variety of areas, as presented in this paper, are necessary for effective research translation and science communication to increase public access to and understanding of environmental health research that impacts decision-making and community resiliency. There are multiple similarities in center investigator and center partner training needs for communication practices (Altman et al. 2020). It is also crucial that scientists and stakeholders collaborate in transdisciplinary partnerships that facilitate

timely information flow, iterative knowledge co-production, and meaningful framing and application for intended audiences, and that they ensure adequate representation of public/community interests at all stages of the research and translation processes. Specific recommendations include incorporating community-engaged and community-based participatory research and knowledge co-production into training, applying these frameworks to improve stakeholder engagement in research partnerships (Winterbauer et al. 2016; Reed and Abernethy 2018; Burwell-Naney et al. 2019), and developing and training investigators and their partners on a systematic approach for engaging their intended audiences (Iwamoto et al. 2019; Mackenzie et al. 2019). Future research on identifying and mitigating individual, institutional, relational, and research-related barriers to investigator-partner engagement from the academic side (Jessani et al. 2018), as well as community-held perceptions and existing knowledge of issues related to oceans and human health and climate change interactions, is warranted for improved science communication and interactions at the local level.

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A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

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A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

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**APPENDIX A. RESULTS PRESENTED BY INTERVIEW QUESTION
AND NUMBER OF CODED RESPONSES**

Main Theme	Interview Questions & Emergent Subthemes	Number of Coded Responses
Organization Background	Q1. Can you please describe the work that you do? How many years of experience do you have working in the field?	54
Work Outcomes	Q2. In your view, what are 1-2 ultimate outcomes of your work?	12
Organization Priorities	Q3. What are some goals (priorities) of your organization?	50
Environmental Health Topics	Q4. Do you work on issues related to the OHHC2I research?	
	HABs	27
	Vibrio Bacteria	3
	Microplastics	9
	Reproductive health	5
	Unregulated Contaminants	3
	Air Quality	5
	Environmental Justice	1
	Infrastructure	2
Communications Practices		
Intended Audiences	Q5. Are you currently working in an organization that communicates about environmental health topics? If yes, who are the intended audience(s) of such communication? Probes: beachgoers; HOAs; community members; other.	
	Scientists	2
	Gen Public	16
	Residents	15
	Specialty Populations	5
	Youth	5
	Policy Makers	11
	Physicians	2
	Academia	3
	Government	14
	Nonprofits	7
	Emergent codes	11
Definition of Community	Q11. In your opinion, how would you define the word 'community' as it pertains to your work?	27
Communication Channels	Q6. What strategies does your organization use to disseminate environmental health information and to specifically reach your intended audiences? Probes: meetings; reports; flyers; rack cards; etc.	9
	Q7. Can you please describe other strategies you have for reaching your audiences?	
	In-Person Communication	10
	Community Representatives	14
	Meetings	20
	Focus Groups	1
	Charettes	1
	Phone calls	4

A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

Main Theme	Interview Questions & Emergent Subthemes	Number of Coded Responses
Communication Channels (<i>continued</i>)	Specific person in the organization	1
	Tour	2
	Career Days	2
	Festival	2
	Video Conferencing	9
	Website	21
	Flyers, Pamphlets, Rack Card	12
	Email	9
	Blogs	7
	Online Training Module	4
	Radio	6
	Reports	7
	Scientific Literature (peer-reviewed)	3
	Social Media	19
	Newspaper articles	11
	Press release	5
	Newsletters	3
	Videos	6
	Television	5
	Advisory Signs	4
Academic Press	2	
Conference	5	
Journal	2	
Dissemination Partners	Q10. Are you currently working or collaborating with any partner organizations to disseminate information about environmental health topics? If so, which organizations and how do they disseminate the information?	
	Academic	17
	Federal Govt	4
	State Govt	16
	Physicians	3
	Local Orgs in Field	6
	Partnerships (Coalitions)	18
	Professional Organizations	15
Ongoing Dialogue	Q17. How does your organization practice an ongoing dialog with its stakeholders? Probe: e.g., stakeholders set agendas and express information needs.	
	General description	19
	Sets agenda	4
	Expresses information needs	3
Measures of Communication Effectiveness	Q9. How do you measure the effectiveness of your organization's communication strategies? Probes: number of website visits, social media metrics, follow up studies to analyze if target audiences understand messages	
	Findings and Changes	7
	Evaluation	21
	Online communication evaluation	10

Main Theme	Interview Questions & Emergent Subthemes	Number of Coded Responses
Communication Challenges		
Challenges in Reaching Audiences	Q8. What challenges do you experience in reaching your intended audiences? Please explain your response.	11
	Impact of COVID on Communication	22
	Technology	5
	Building relationships	6
	Mistrust	2
	Working with public	10
	Better and more timely communication between entities	4
	Working with others	2
	Time constraints	3
Perceptions of Research Translation		
Definition Research Translation	Q12: In your opinion, what is “research translation”?	21
Communicating about Uncertainty		
With Scientists	Q19. What is your experience communicating with scientists about uncertain research findings?	19
With Intended Audience	Q20. How comfortable do you feel communicating with your intended audiences about uncertain research findings? Why?	26
Collaboration with Scientists		
Science Data Sources	Q13: Where do you typically get data about environmental health topics? a. Probes: Generate in the organization; directly from an in-person source; a government data source; publications; etc.	
	Primary Data (Generated in the organization)	10
	Secondary Data	
	Federal	11
	State	6
	Academic	7
	Scientific literature	4
	Partnerships	6
	Scientific Community	3
Working with Scientists	Q14: Can you describe your experiences working with scientists and how they share research findings with you and/or your organization?	27
Providing information needs to researchers	Q15. Can you describe your experiences with being asked to provide information needs to researchers at the beginning of a project?	17
Ongoing Dialogue	Q16. Is there encouragement for an ongoing dialog with researchers vs. being the recipient of information after it is generated? Please explain.	17
Timing of Results Dissemination	Q21. In your opinion, when should scientists disseminate the results of their studies? a. Probes: while in progress; after completed; only after published in scholarly journal; etc.	
	While in progress	5
	After completed	6
	After published	7
	Report Back to Community	2
	Ongoing process	6

A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

Main Theme	Interview Questions & Emergent Subthemes	Number of Coded Responses
Preference for Receiving Research Finding	Q22. How would you like to receive information about research findings? Probes: content and format	
	One-pager	3
	Peer-review	7
	Pre-digested	6
	Social media	0
	Full report	6
Nested levels	3	
Training in Science Communication and Research Translation		
Past Training	Q23. What type of training, if any, have you had in research translation or science communication?	26
Training Needs	Q24. What type of science translation training might be you interested in?	20
Science Communication Needs	Q18. What are your organization's science communication needs, if any?	17
Emergent Topics		
Alarmist Response	6	
Plain Language	11	

APPENDIX B. REPRESENTATIVE QUOTES ABOUT COMMUNICATION CHANNELS

Main Communication Channels	Number of Mentions	Representative Quotes
Websites	21	<i>So within—we share a lot of information through our [agency branch name] webpage, also. Sometimes, it's hard to find because our webpages are continually being updated. You know, so, as a large agency, your key partners need to know who you are, and we work with them very well to let them know where the links are, the information. I 03</i>
		<i>And there's a website that tries to keep up with what are the big occurring health concerns in different parts of the state and in general the different ethnic groups that may be more impacted by certain things than others. I 04</i>
Social Media	19	<i>We have an official [program name] Twitter and Facebook presence. And as I said, the agency itself has Twitter and Facebook accounts. I 04</i>
		<i>We use social media. [Name of the organization] has a Twitter account, so we put information out on Twitter pretty much daily. And with Twitter, that's pretty easily consumable. And if you want to dig deeper into stuff, you can get there through Twitter or you can just quickly consume what we put out there. I 06</i>
Flyers, Pamphlets, Rack Cards	12	<i>Instead of talking verbally to people when we're in their meetings, we have handouts that we give to them. We have turned to using infographics a lot to explain very complex issues, concerns. I 01</i>
		<i>Yeah. We have a couple of brochures that—and that's just happened this year. But it's basically like what is algae? What causes it? How do I deal with it? Can I touch it? Should my pets deal with it? And that sort of thing. So, that's out there and those have been disseminated through email to all of the [organization] membership. There are a couple of those. I 05</i>
Newspaper Articles	11	<i>We've done—there was a small newspaper on Lake Wateree and we've published numerous articles and communicated back through that way. I 05</i>
		<i>I will generally do an editorial or put an opinion piece out for newspapers across the state about the [conference name]. I 06</i>
In-Person Communication		
Meetings	20	<i>We host community and public meetings, and we use our coordinator to host those. I 03</i>
		<i>Two-day kind of events where we take a tour of communities to learn more about their concerns from their perspective as well as have a full-day kind of facilitated conversation with the communities about their priorities and strategies to—and prioritize on those concerns and identify some strategies in which we could address some of their concerns during that two-day interaction. I 01</i>
Community Representatives	14	<i>We walk our communities frequently just to engage residents on a one-on-one basis and get to know them on a personal level. I 01</i>
Phone Calls	4	<i>But my general work with the public is people calling me with questions about what's the water quality of this pond on this property I'm looking at and what are my concerns and how do I get water samples tested. And so that tends to be more my interaction, is more one-on-one. I 04</i>
Tour	2	<i>They would often have plant tours and bring the general public in to be able to view their plant. I 08</i>
Career Day	2	<i>When I've talked to schools and school groups and guidance counselors they largely don't know that these careers even exist. So as we talk to those groups that's helping to inform them about the work that's actually done, and also hopefully recruit some younger people to be interested in professions in the water industry. I 08</i>
Festival	2	<i>A water festival. So those are all opportunities to help educate folks about water and how it's used and why it needs to be protected. I 08</i>

A Qualitative Study of Environmental Health Partners' Communication Practices and Needs

Main Communication Channels	Number of Mentions	Representative Quotes
Focus Groups & Charettes	1 & 1	... we use focus groups, we use charettes. I 01
Specific Person in the Org.	1	And, in addition, within the [organization] we have a Public Participation Coordinator ... and she is our person if communities have concerns and needs. And we work individually with our Public Participation Coordinator to do a lot of communication, outreach and education. I 03
Email	9	<p>Our weekly updates involve sending flyers to the community presidents as well as links embedded into e-mails that we sent the community presidents that send them directly to, for example, infographics or statistics that we wanna share with them. We send links instead of us trying to explain it in a long e-mail about what it is that we're trying to communicate with them. We now use infographics and links and things like that so that they can follow up with—if they wanna do deeper dives in the information. So those are some of the things that we have worked on. I 01</p> <p>And we sometimes do email pushes with information too, I guess primarily using MailChimp to get information out to people who have given us their email addresses and asked for information. We have a big list—I guess it used to be a listserv. I don't know if it's called that anymore. But again, we'll push information out through MailChimp to get to people that we're kind of more directly connected to. I 06</p>
Other Communication Channels		
Video Conferencing	9	Online platforms like GoToMeeting, Zoom, those types of platforms. I 01
Blogs	7	Right now all I have is the blog, and I really try to think very carefully about what I say in the blog. I 02
Radio	6	I did get on a radio program, you know, for the general public, maybe about a year and a half ago here in Utah to talk about the issues. I 02
Reports	6	We also have something called [Organization] Weekly Reports that come out. And [partner organization] has quarterly reports that come out. So, we have a lot of reporting that come out for the general public. I 07
Videos	6	<p>So we have a course actually, and I'm trying to remember exactly how many sessions there were but it was like maybe eight sessions or something like that. It's online, it's video, it's content, it's—and it's got some quizzes and all that kinda thing in it. And so that's going to be available to the public. I 02</p> <p>So we really are trying very hard to make the information available to the public through videos, online, through just educational things. I 02</p>
Press Release	5	Trying to do press releases as much as possible and get to the local news outlets. I 09
Television	5	I was interviewed by anything from Fox News to CNN to Discovery. It was—ran in like 280 different newspapers. I was also interviewed for Discovery has this show called—what's it called now? It's been a few years. It's a show called What on Earth? I was actually interviewed on that and I was on like 3 or 4 of their episodes talking about weird things about like a bloom or a—something that they found from outer space that looked odd. So, it was kind of interesting to be on TV doing something like that. I 07
Conference	5	Our association has limited staff and yet we put on 20-24 workshops and major conferences. Our annual conference, [name of the conference], is a big annual conference the size of some national conferences. It's about 1,600 people, 250 vendors. I 08
Advisory Signs	4	<p>We've got close to 500 signs at all the beach access points for people to see which _____ beach. It's not a, "Oh, by the way, check here for a swimming advisory" or anything. It's, "Here, check for beach information." So it's kind of that consistent language for flags on the beach, swimming issues. I 09</p> <p>Signs at the affected areas. I mean it's probably one of the most targeted pieces that we do. So you target those that may be accessing a water body. I 09</p>

Main Communication Channels	Number of Mentions	Representative Quotes
Scientific Literature (Peer-Reviewed)	3	<i>So I guess we use all the traditional academic avenues of information dissemination. So there are academic journals, peer-reviewed journals, non-peer-reviewed journals. We also publish through our university press and our cooperative extension service. . . . And the extension service tends to publish more materials for the non-science audience. I 06</i>
Newsletters	3	<i>We advertised it in some of the newsletters and things from the neighborhoods. I 02</i>
Academic Press	2	<i>We have a journal of [name of the journal] that our university press puts out. I 06</i>
Association Journal	2	<i>We publish a journal every quarter. And our journal magazine has technical content and educational material. I 08</i>



NPDES Phase II Stormwater Rule—Integrating Community Engagement and Engineering Education

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Abstract. The Engineering Program at Coastal Carolina University seeks to train future leaders who will develop and implement sustainable solutions to global challenges by engaging students in real-world, community-based projects starting with the two-course Cornerstone Sequence. The program’s vision is to: (1) increase participation of underrepresented and minority groups and address the persistent degree attainment gap in engineering; (2) create a learning and professional environment where diversity is celebrated as seminal to program success and where all students, particularly underrepresented and minority groups, thrive and excel; and (3) develop future leaders who are knowledgeable and who are able to apply scientific and engineering principles to impact the well-being of the global society and its environment. The Coastal Waccamaw Stormwater Education Consortium (CWSEC) members include six citizen science education agencies and eight municipal separate storm sewer systems (MS4s) serving Horry and Georgetown Counties in South Carolina. The mandate of the consortium is to help local governments meet EPA’s National Pollutant Discharge Elimination System (NPDES) Stormwater Management Program Phase II Rule by implementing the following Minimum Control Measures (MCM): (1) Public Education and Outreach on Stormwater Impacts, and (2) Public Participation/Involvement. The consortium and the Engineering Program have partnered on MCM (1) and (2) by: (i) Integrating consortium activities in the ENGR 199/299 Cohort Grant Challenge Cornerstone Course Sequence’s deliverables. The objective of this two-course sequence is for students to identify and formulate complex engineering problems utilizing the National Academy of Engineering’s (NAE) 14 Grand Challenges for Engineering in the twenty-first century as a framework for community-based projects; and (ii) Collaborating with representatives from municipalities and educational providers that are members of the consortium to provide current stormwater-related engineering design challenges to student groups. This paper reports on an initial, successful prototype of this partnership that occurred during the 2020 fall semester. Projects were focused on various aspects of the NAE Grand Challenge—“Provide Access to Clean Water.” The long-term vision is to integrate consortium activities into the engineering curriculum while leveraging the talent of engineering students to solve stormwater challenges in the community.

INTRODUCTION

One of the main objectives of the Clean Water Act (CWA) is to promote public health by reducing pollution in the nation’s water bodies. Stormwater runoff is a major cause of nonpoint source pollution resulting in water quality deterioration in the urban water cycle (Ma et al. 2018). Stormwater runoff is most sensitive to significant variations in impervious surfaces, which results from rapid urbanization and subsequent land-use changes (Gold et al. 2017; Shukla et al. 2018; Yang and Toor 2018). Over the last decade, coastal counties experienced increases in population density over three times the national average (Freeman et al. 2019). Further, these communities are more susceptible to storms and concomitant surface water pollution due to runoff; their

close proximity to the sea means higher rainfall intensity for the same design storm and they are generally flat, which increases the time of concentration (i.e., water stays in communities longer).

More frequent extreme weather and obsolete or non-existent stormwater management regulations, combined with rapid development, have increased stormwater runoffs, resulting in expensive and sometimes catastrophic flooding, as well as water quality issues. These challenges are especially relevant to South Carolina’s Coastal Plain (Blair et al. 2016). In the last few years, the area has been affected by at least one major hurricane with subsequent flooding. The pace of development is accelerating, and the resulting floods affect low socioeconomic status areas at higher rates and greater intensity (Dickes et al. 2016; Ellis et al. 2017; Kuhl 2019; Mal-

lin et al. 2019; Schroer et al. 2018). Horry and Georgetown Counties are two of eight coastal counties in South Carolina. Horry County is the second-fastest-growing Metropolitan Statistical Area in the country; its population and its housing development have doubled in the last three decades and are on pace to double in the next 20 years. Georgetown County’s population grew over 601% within a 40-year period. Both counties constitute the Grand Strand, which sees up to 18 million tourists annually (Horry County Government 2019). The continual growth as a tourist attraction naturally leads to land development to support the economy and concomitant increases in impervious surfaces.

Urban development and resulting stormwater discharges are regulated under the CWA’s National Pollutant Discharge Elimination System (NPDES) permit program. The program made it illegal to discharge any pollutant as a point source into waters of the United States without an NPDES permit (US EPA 2005). While unique origins of stormwater and subsequent *in situ* pollutants are technically nonpoint sources, runoff flows are defined by the South Carolina Department of Health and Environmental Control (SCDHEC) as point sources under the South Carolina Pollution Control Act and therefore requires an NPDES permit (Pollution Control Act of 1962). The CWA initially focused on industrial and municipal sewerage systems, but it was expanded to also include pollutants reduction in stormwater systems (Pines 2005). Phase II of the two-phase Stormwater Rule was published in December 1999 and focused on small Municipal Separate Storm Sewer Systems (SMS4s). The Phase II program includes six Minimum Control Measures (MCMs):

- Public Education and Outreach on Stormwater Impacts
- Public Involvement and Participation
- Illicit Discharge Detection and Elimination
- Construction Site Stormwater Runoff Control

- Post-Construction Stormwater Management in New Development and Redevelopment
- Pollution Prevention and Good Housekeeping for Municipal Operations

The Coastal Waccamaw Stormwater Education Consortium (CWSEC) is one of three regional consortia serving South Carolina’s eight coastal counties. CWSEC members include six citizen science education agencies and eight municipal separate storm sewer systems (MS4s) serving Horry and Georgetown Counties (see Table 1). CWSEC was formed in 2004 to facilitate regional collaboration of stormwater educational efforts in response to current and future requirements. The mandate of the consortium is to help local governments meet EPA’s National Pollution Discharge Elimination System (NPDES) Stormwater Management Program Phase II Rule by implementing the first two of the six Minimum Control Measures (MCM):

- Public Education and Outreach on Stormwater Impacts
- Public Participation and Involvement

About 50% of the engineering majors at Coastal Carolina University identify as underrepresented minorities. In today’s increasingly global economy, there is an urgent need for a diverse engineering workforce (Gray and Lundy 2016). However, according to the American Society for Engineering Education’s “Going the Distance” report, 53.6% of Hispanic, 61.4% of Native American, 61.7% of African American, and of 49% female students who enter engineering programs do not graduate in this major (ASEE 2012). This translates to an engineering workforce comprised of about 6% Hispanics, 0.3% Native American, 4% African Americans, and 13% females, according to the latest National Science Foundation’s report (NSF 2019). With such high attrition rates among minorities and underrepresented groups, changing the current engineering workforce’s diversity portfolio is of grave

Table 1. Coastal Waccamaw Stormwater Education Consortium Members

Citizen Science Educational Providers	Municipal Separate Storm Sewer Systems (MS4s)
1. Coastal Carolina University’s Waccamaw Watershed Academy	1. Horry County
2. Clemson’s Carolina Clear	2. City of Conway
3. Murrells Inlet 2020	3. Georgetown County
4. North Inlet-Winyah Bay National Estuarine Research Reserve (NERR) Coastal Training Program & Public Education Program	4. Town of Surfside Beach
5. South Carolina Sea Grant Consortium	5. City of North Myrtle Beach
6. Winyah Rivers Foundation Waccamaw Riverkeeper Program	6. City of Conway
	7. Town of Atlantic Beach
	8. Town of Briarcliffe Acres

national importance and requires a plethora of high-impact approaches. Successful high-impact practices include introducing design and research early and partnerships with local communities to positively affect interest and persistence in engineering programs, thereby strengthening the educational pipeline (Chang 2002).

The Engineering Program at Coastal Carolina University seeks to train future leaders who will develop and implement sustainable solutions to global challenges by engaging students in real-world, community-based projects starting with the two-course Cornerstone Sequence. The program's vision is to: (1) increase participation of underrepresented and minority groups and address the persistent degree attainment gap in engineering; (2) create a learning and professional environment where diversity is celebrated as seminal to program success and where all students, particularly underrepresented and minority groups, thrive and excel; and (3) develop future leaders who are knowledgeable and who are able to apply scientific and engineering principles to impact the well-being of the global society and its environment. As a graduation requirement, each student must complete at least one experiential opportunity that fulfills the following ABET accreditation student outcomes: (1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics; and (2) an ability to apply engineering design to produce solutions that meet specified needs with consideration for public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

This paper reports on a case study of an initial partnership prototype between the CWSEC and the Engineering Program that occurred during the 2020 fall semester. The partnership synergistically leveraged the consortium's mandate to help local governments meet MCMs (1) and (2) to educate and involve the public with the Engineering Program's goals to introduce design and research early in the curriculum as a retention practice. Projects were focused on various aspects of the National Academy of Engineering (NAE) Grand Challenge for Engineering in the Twenty-First Century—"Provide Access to Clean Water." This challenge focuses on new threats, such as stormwater, to the world's water supplies and the need for global solutions (NAE 2021). The long-term vision is to integrate consortium activities into the engineering curriculum while leveraging the talent of engineering students to solve stormwater challenges in the community. The target audiences for this work includes MS4s and stormwater consortia who are exploring ways to satisfy NPDES MCMs (1) and (2) and engineering faculty and students seeking ways to connect the academic classroom experience with real-world challenges and opportunities, particularly in the area of stormwater management and control.

BACKGROUND AND RELATED WORK

In its 2000 Fact Sheet series on Stormwater Phase II Final Rule (EPA, 2005), the EPA discussed why it was necessary to have MCMs (1) and (2). That information is summarized as follows:

1. Public Education and Outreach on Stormwater Impacts—an educated community is integral to successful stormwater management because it fosters greater support and compliance as a result of increased understanding and subsequent ownership among citizens.
2. Public Participation and Involvement—encourages valuable inputs and an active role in the development and implementation of watershed-based stormwater management plans. This allows for broader public support, shorter implementation schedules, a treasure trove of intellectual resources, and the potential for braiding of resources from other community and government programs.

Over the last sixteen years, the consortium has fulfilled its mandate via a number of activities, such as:

- Public Education and Outreach on Stormwater Impacts
- Classroom education on stormwater
- Education displays, pamphlets, and other stormwater educational materials
- Low-impact development training
- Pet waste management
- Using the media
- Public Participation and Involvement
- Reforestation programs
- Stakeholder meetings
- Storm drain stenciling
- Stream cleanup and monitoring
- Volunteer monitoring

The consortium has previously engaged undergraduate students through its Campus Volunteer Water Quality Monitoring program. The goal of the program is to provide an assessment of water quality conditions in the stormwater ditches and retention ponds on campus, all of which eventually send waters off campus toward the Waccamaw River, a slow-moving, blackwater river and one of the primary sources of drinking water in Horry County. Sampling is conducted weekly during the academic semesters. The data are being used to evaluate whether water quality is improving or degrading over time at some or all the sites using a watershed

approach. This project is a natural progression of the past iteration of the Campus Monitoring Program whereby the activities are integrated into the courses and curriculum of the newly developing engineering program, simultaneously fulfilling curricular and compliance requirements while expanding to include community members.

PROJECT OBJECTIVES/GOAL

The goals of the project are:

- Initiate collaboration between the CWSEC and the Engineering Program to:
- Increase participation of underrepresented and minority groups and address the persistent degree attainment gap in engineering;
- Create a learning and professional environment where diversity is celebrated as seminal to program success and where all students, particularly underrepresented and minority groups, thrive and excel; and
- Develop future leaders who are knowledgeable and are able to apply scientific and engineering principles to impact the well-being of the global society and its environment.
- To train future engineering leaders by engaging students in real-world community-based projects and assessing the following ABET student outcomes:
 - An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics; and
 - An ability to apply engineering design to produce solutions that meet specified needs with consideration for public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
 - Help local governments meet EPA's National Pollution Discharge Elimination System (NPDES) Stormwater Management Program Phase II Rule by implementing the first two of the six Minimum Control Measures (MCM); namely:
 - Public Education and Outreach on Stormwater Impacts
 - Public Participation and Involvement.

MATERIALS AND METHOD

Nine (9) groups of 2 to 3 engineering students/designers were assigned community-based stormwater-related projects as well as community client(s). Their goals were to work with

clients to determine the need/problem, formulate problem and design statements, and propose solutions. As a result of the ongoing COVID-19 pandemic, all interactions were done virtually via emails and videoconferencing. At the end of the semester, students, clients, faculty, and other community members participated in a virtual cornerstone colloquium, where student groups presented their work. The consortium and Engineering Program, therefore, partnered on MCMs (1) and (2) by:

- Integrating consortium activities in the ENGR 199/299 Cohort Grant Challenge Cornerstone Course Sequence's deliverables. The objective of this two-course sequence is for students to identify and formulate complex engineering problems utilizing the National Academy of Engineering's 14 Grand Challenges for Engineering in the 21st century as a framework for community-based projects. Projects, including a collaboration with Georgetown County Stormwater, focused on various aspects of the Grand Challenge—"Provide Access to Clean Water."
- Collaborating with representatives from municipalities and educational providers who are members of the consortium to provide current stormwater-related engineering design challenges to student groups.

RESULTS

The course description was as follows: Great engineering achievements such as safe drinking water and electricity have revolutionized society. While these achievements are remarkable, future engineers are faced with many more great challenges and opportunities yet to be realized. With input from people around the world, an international group of leading technological thinkers were asked to identify the Grand Challenges for Engineering in the twenty-first century. Their 14 game-changing goals for improving life on the planet, are introduced in this course as a means introducing complex engineering problems, how to identify and formulate them by applying principles of engineering, science, and mathematics.

The resulting projects are summarized in Tables 2 through 10.

NPDES Phase II—Integrating Community Engagement and Engineering Education

Table 2. Project #1: Water Treatment in the Time of Hurricanes—Bull Creek Regional Water Treatment Plant

Project Title	Project #1: Water Treatment in the Time of Hurricanes—Bull Creek Regional Water Treatment Plant
Community Client/ Technical Advisor (s)	Grand Strand Water and Sewer Authority
Target Consumers/ Stakeholders	Water Treatment Operators, SCDHEC and Water Customers in the Community
Project Scenario & Context	<p>The Bull Creek Regional Water Treatment Plant can treat as much as 45 million gallons of water each day. Untreated surface water is pulled from Bull Creek, which is an arm of the Great and Little Pee Dee Rivers. The turbidity, color, organics, and other water quality pollutants are different in each tributary and must be considered in the water treatment process. The water quality in the Little Pee Dee is characterized by high tannins, fulvic and humic acids (high color and organics), and low turbidity. While the water from the Great Pee Dee River has less color and organic content (i.e., easier to treat), it has more solids that result in higher turbidity. During normal flows, the proportion of water volumes from the Great Pee Dee tributary and Little Pee Dee tributary into Bull Creek is approximately 4:1, respectively. During heavy rainfall events, the volumetric flow proportion changes sometimes flip from 4:1 to 1:4 because the Little Pee Dee is closest to the coast and receives more rainfall during localized rain events. This wild swing in volumetric flow results in a drastic change in the quality of the raw water and thus the dosing of treatment chemicals. During normal flows, the Environmental Quality Lab on site at the Bull Creek plant runs Total Organic Carbon (TOC) analysis to determine the dosing requirements each day. In response to heavy rainfall events when the water quality is rapidly changing, sometimes hourly, Water Treatment Operators must figure out a way to quickly determine the concentrations of pollutants in the treatment plant's influent in order to effectively treat the raw water and produce high-quality, safe drinking water for the community.</p>
Problem Statement	<p>The quality of raw water entering Water Treatment Plants (WTP) changes continually and more drastically during storm events. TOC is the total amount of organic carbon in natural waters and can combine with disinfectants to create carcinogenic a Disinfectant By-Product. TOC removal is therefore regulated by law, and the water treatment process must be optimized to ensure high-quality and safe, potable water to customers. While the Jar Test Method is the gold standard for determining the concentration of TOC present and the optimal coagulant and dosage for a WTP's raw water, it takes a long time and requires qualified laboratory technician skills that are not always available, especially during storm events.</p>
Design Statement	<p>The Team is tasked with exploring rapid and easy-to-use substitute(s) or surrogate(s) to the Jar Test Method for TOC analysis. The new Method (s) should be fast, easy for WTP Operators to learn and carry out, and must be as effective and accurate as the Jar Test Method. Ideally, it will employ current water quality analysis methods already carried out by WTP Operators.</p>

Table 3. Project #2: Treating Conway's Wastewater—Managing Filamentous Microbial Growth in Sewer Lines

Project Title	Project #2: Treating Conway's Wastewater—Managing Filamentous Microbial Growth in Sewer Lines
Community Client/ Technical Advisor (s)	Grand Strand Water and Sewer Authority
Target Consumers/ Stakeholders	Wastewater Treatment Operators, Community Residents, SC DHEC, Riverkeeper
Project Scenario & Context	<p>The Conway Wastewater Treatment Plant (WWTP) serves the city of Conway and a large portion of the western areas of Horry County, and it is rated to treat up to 4.0 million gallons of wastewater per day. The treated effluent is discharged into a swampland on the Waccamaw River, which is a drinking water source for the county and historically suffers from low dissolved oxygen levels. The wastewater treatment process starts as soon as it leaves homes and businesses. This is because the microorganisms that naturally occur in wastewater play an important role in the wastewater treatment process. Therefore, the time spent in the water, the flow rates and volumes moving through the collection system, and the pollutants in the wastewater stream impact the treatment process at the plant. For example, warmer or colder weather or the presence of grease can significantly change the microbial species, concentrations, and activities, which in turn, affects the treatment process. Cities like Conway and Wastewater Treatment Operators need ways to quickly determine and anticipate changes in pollutants and microbial makeup of the influent flowing into WWTPs if they are to effectively treat it before discharging to the environment.</p>
Problem Statement	<p>As sewage is transported in the hundreds of miles of the urban sewer pipe infrastructure, microorganisms proliferate and become a part of the influent flow to Conway WWTP. These microorganisms in general are beneficial and are employed in the treatment process; however, some, particularly filamentous microbes, can adversely impact the removal of pollutants from the wastewater. WWTPs require low levels of filamentous microorganisms because an overabundance causes sludge bulking, pin-floc/poor flocculation, foaming (biological), rising solids (denitrification), and ultimately poor settling of solids. This in turn results in increased treatment cost and poor effluent quality to receiving water bodies, such as the Waccamaw River, which is a drinking water source for the county and which historically suffers from low dissolved oxygen levels.</p>
Design Statement	<p>The Team has been tasked with researching and proposing ways to effectively predict and manage growth of filamentous microbes in sewer lines in transit to the Conway WWTP. This solution needs to reduce the proliferation of filamentous microorganisms while simultaneously increasing aerobic bacteria concentrations. If possible, the solution should not only solve the problem of the overabundance of filamentous bacteria in the collection system but also determine the cause of the overabundance to ensure future predictions. The solution should not simply be a maintenance correction, but rather a permanent answer to the problem. The proposal needs to be completed by December 4 and it must be cost-efficient. The solution should ensure compliance with SCDHEC standards per the WWTP's operation permit for effluent discharged to the Waccamaw. The Team must also prepare an innovative and creative educational and outreach program for management of Fats, Oils and Grease (FOGs) specific to the communities in the treatment area of the plant.</p>

NPDES Phase II—Integrating Community Engagement and Engineering Education

Table 4. Project #3: Covington Lake—Pond Volume Assessment and Simulation

Project Title	Project #3: Covington Lake—Pond Volume Assessment and Simulation
Community Client/ Technical Advisor (s)	Covington Lake Homeowners Association (HOA), Residents and Board
Target Consumers/ Stakeholders	Covington Lakes Homeowners, Covington Lakes HOA
Project Scenario & Context	<p>The Covington Lake Subdivision off Carolina Forest Boulevard in Myrtle Beach, South Carolina, has 4 stormwater retention ponds. All water runoff from any street or the 147 lots in the development goes to the retention ponds. The purpose of these ponds is to slow and treat the runoff to prevent flooding and pollution downstream through storage, evaporation, sedimentation, infiltration, and controlled discharge over time. In addition, the lakes provide beauty, home for wildlife, and recreational fishing. The residents and the HOA Board recognize that maintenance of the lakes is a high priority to ensure that the water being stored and being sent down to the ocean/river is as pollution-free as possible. In addition, preservation of the pond depth through the control of erosion is important to maintain the storage capacity of ponds. During an HOA Board workshop on March 4, 2020, Total Lake, the contracted pond management company, reported that the condition of the ponds is quite good. The depth is, for the most part, 4 feet deep (required by Horry County). Total Lake reported that the lake bottoms generally had very little silt and were hard. Engineering design requirements for stormwater retention ponds are based on 25- and 100-year storms, but more frequent and intense storms have become increasingly common in the last few years. Thus, the current required depth might not be enough. Also, the ponds are decades old, and the depth might have changed over time. It is therefore important to determine the actual pond volume.</p>
Problem Statement	<p>The Covington Lakes Subdivision and its stormwater retention ponds were developed over 25 years ago, when the design code for ponds required storage for 25-year storms and 100-year storms were not enacted. Higher-intensity storms (e.g., 500-year events) are becoming more frequent. Moreover, the sedimentation and erosion may have reduced pond depth and subsequently total capacity. It is therefore necessary to assess the accurate volume of the ponds to inform future management decisions, ensure homeowners safety and peace of mind, and develop a community outreach plan to drive participation in protecting and preserving the ponds.</p>
Design Statement	<p>The Team has been tasked with surveying the stormwater retention pond adjacent to Carolina Forest Blvd. and Covington Lakes Dr.; provide AutoCAD drawings of pond; calculate pond's volume precisely; determine seasonal water levels (low water level, high water level, and normal water level); simulate pond levels during 10-year, 25-year, 50-year, 100-year, and 500-year storms; and create a community education and outreach plan to inform community members and drive participation in protecting and preserving the ponds.</p>

Table 5. Project #4: Reducing Stormwater Impacts on Water Quality in Shellfish Harvesting Areas—A Pervious Pavements Installation Approach

Project Title	Project #4: Reducing Stormwater Impacts on Water Quality in Shellfish Harvesting Areas—A Pervious Pavements Installation Approach
Community Client/ Technical Advisor (s)	Public Works Department, City of North Myrtle Beach (Stormwater)
Target Consumers/ Stakeholders	City of North Myrtle Beach, Horry County and Surrounding Communities
Project Scenario & Context	In 2016, the SCDHEC funded the Waccamaw Regional Council of Government (COG) with a \$21,000 grant to develop a watershed-based management plan. COG worked with North Myrtle Beach, Horry County, and Coastal Carolina University to evaluate bacteria levels from the Intracoastal Waterway to the beach in the Cherry Grove, Hog Inlet, Dunn Sound Creek and Little River Neck areas. Hog Inlet and Dunn Sound Creek are designated as Shellfish Harvesting Waters by the SCDHEC and are located within the Shellfish Program’s Management Area 01; therefore, fecal coliform bacteria is the primary water quality standard monitored. In 2018, COG completed the plan, detailing several recommendations on how to control the bacteria with the end goal of increasing shellfish harvesting again. As a result, COG was awarded a 319 grant to implement the plan. Recommendation F-15 from the plan proposed the installation of pervious surface parking lots and streets throughout the watershed. The Client requested that the Team explore potential locations to install pervious pavement on the last 50–100 ft sections of each of the dead-end streets in the Cherry Grove Beach area. Targeted catchment areas are East Cherry Grove, Seas Mountain Highway, Hill Street, and Little River Neck Marsh.
Problem Statement	The 2017 Shellfish Management Area 01 Annual Update reveals that none of the monitoring sites met the standard for designated use. As of the SCDHEC’s 2015 Annual Update report, all designated shellfish habitats within Management Area 01 are restricted or prohibited to shellfish harvesting. The watershed-based plan identified the sources of the fecal coliform impairments (e.g., stormwater runoff) and proposed strategies to help improve water quality in the Hog Inlet–Dunn Sound Creek area. The drainage system within the Cherry Grove Beach area does not have a conventional curb, gutter, and drainage ditch storm sewer system. Instead, during storm events, precipitation runs off as sheet flow across the landscape, particularly along impervious surfaces. More pervious pavement areas are needed to increase stormwater runoff infiltration into the ground surface prior to it reaching the estuary shoreline.
Design Statement	The Team is tasked with exploring potential locations to install pervious pavement on the last 50–100 ft sections of each of the dead-end streets in the Cherry Grove Beach area. The Team must identify/prioritize at least 3 site-specific locations within the Cherry Grove area to design, permit, and install areas of pervious pavement at the identified locations. The potential pervious pavement areas are not necessarily limited to street ends. The areas chosen for pervious pavement installation must be: (1) be owned and maintained by the city, and (2) receive and filter stormwater runoff to have a positive impact on water quality within Hog Inlet and Dunn Sound Creek. Targeted catchment areas are East Cherry Grove, Seas Mountain Highway, Hill Street, and Little River Neck Marsh.

NPDES Phase II—Integrating Community Engagement and Engineering Education

Table 6. Project #5: Simultaneously Restoring a Windy Hill’s Saltwater Marsh and Preserving Briarcliffe Acres’ Freshwater Ponds—Stabilizing White Point Swash Approach

Project Title	Project #5: Simultaneously Restoring a Windy Hill’s Saltwater Marsh and Preserving Briarcliffe Acres’ Freshwater Ponds—Stabilizing White Point Swash Approach
Community Client/ Technical Advisor (s)	Public Works Department, City of North Myrtle Beach (Stormwater)
Target Consumers/ Stakeholders	North Myrtle Beach, Horry County, and Briarcliffe Acres
Project Scenario & Context	North Myrtle Beach, Horry County, and Briarcliffe Acres have been studying erosion, flooding, and poor water quality within the marsh and at the interface between the marsh, ocean, and freshwater pond system. The salt marsh experienced significant loss of marsh grass 2 years ago. Streets near the marsh experience flooding during high tide (King Tide) and during excessive rain events. Briarcliffe Acres experiences loss of the dune system along the beachfront to the extent that freshwater ponds are potentially exposed to ocean wash-over. Horry County periodically maintains the swash opening to the ocean, which requires substantial construction on the beach.
Problem Statement	Streets near the Windy Hill Marsh, a saltwater marsh, experience flooding during high tide (King Tide) and during excessive rain events. Flooding and erosion from surrounding roadways and developments cause freshwater and sediments to enter the saltwater marsh. Poor stability in the White Point Swash prevents saltwater from going up into saltwater Windy Hill Marsh, resulting in the dying out of marsh grass and critical habitats. The poor stability of the White Point Swash and the loss of Briarcliffe Acres dunes system increases the potential for ocean water wash-over into freshwater ponds. North Myrtle Beach, Horry County and Briarcliffe Acres need sustainable solutions to the flooding, erosion, poor water quality, and unstable swash and dune systems to preserve critical habitats and ecosystems of the Windy Hill saltwater marsh, as well as the freshwater pond system in Briarcliffe acres.
Design Statement	The Team has been tasked with proposing solutions (1) to street flooding near Windy Hill Marsh and associated water quality issues in the marsh; (2) to increase White Point Swash stability, subsequently allowing saltwater back into the marsh to reestablish marsh grass and ecosystem; and (3) to prevent saltwater from entering the freshwater pond over in Briarcliffe Acres.

Table 7. Project #6: Toward Developing a Watershed-Based Plan for Edisto Island

Project Title	Project #6: Toward Developing a Watershed-Based Plan for Edisto Island
Community Client/ Technical Advisor (s)	Department of Forestry & Environmental Conservation Clemson University Extension
Target Consumers/ Stakeholders	Citizens of the Town of Edisto Beach
Project Scenario & Context	<p>The Edisto River Basin is the watershed for the Edisto River, one of the longest free-flowing blackwater rivers in North America. The lower part of the Edisto River Basin joins with the Ashepoo and Combahee River Basins to create the ACE Basin, an estuary of national significance. Land use across Edisto Island is mostly rural with low-density residential and agricultural activities predominating. The 3 sub-watersheds of focus—Store Creek, the South Edisto River-Atlantic Intracoastal Waterway, and the Dawho River-North Edisto River—span Edisto Island and the town of Edisto Beach and are part of the larger Edisto River Basin. The town of Edisto Beach, a 6-mile-long barrier island made up of approximately 25% salt marsh, is a beachfront community with a small population of full-time residents that experiences a seasonal influx of tourists; it also includes a 1,200-acre state park that hosts both cabins and campsites. Many of the waterways around Edisto Island and the town of Edisto Beach have high levels of bacteria that exceed safe levels for their designated use. There are 2 Total Maximum Daily Load (TMDLs) in place for bacteria, and around 24 sites are also on the 303d list for bacteria and/or sediment. Nearly 70% of the shellfish beds across the 3 sub-watersheds encompassing Edisto Island and Edisto Beach are closed to harvest.</p>
Problem Statement	<p>Waterways of the town of Edisto Beach and its surrounding watershed have pollution levels that exceed safe levels for designated use; there are 2 TMDLs in place for bacteria, around 24 sites are on the 303d list for bacteria and/or sediment, and nearly 70% of the shellfish beds are closed to harvest. The community needs to create a watershed-based plan for the Edisto Island Watershed that will provide a roadmap to help the community manage pollution problems, restore impaired water bodies (so that all users can enjoy both consumptive (shellfish and finfish harvest) and nonconsumptive (water-based recreation, scenic viewshed, wildlife viewing) uses, and sustainably implement practices to protect the overall health of the connected local and downstream watersheds, which combines to create the Ashepoo, Combahee, and Edisto River (ACE) Basin, an estuary of national significance.</p>
Design Statement	<p>The Team is tasked with the first 3 of 9 essential stages of developing a watershed-based plan for the Edisto Island Watershed. The Team is required to identify the primary sources of pollutants, identify potential management measures or best management practices (BMPs) to implement across the watershed, and estimate the pollution removal potential of installing those BMPs. Finally, due to budgetary constraints, the Team must provide a project prioritization and justification rubric to help community stakeholders decide on an implementation action plan. The recommendations provided as part of this project will inform the next 6 stages of the watershed planning process. Once the watershed-based plan is complete, projects identified in the plan may be eligible for EPA's 319 funds. The project's design brief is due by December 4, 2020.</p>

NPDES Phase II—Integrating Community Engagement and Engineering Education

Table 8. Project #7: Horry County Administration and Courthouse Building's Stormwater Detention Pond #4 Conversion to Raingarden

Project Title	Project #7: Horry County Administration and Courthouse Building's Stormwater Detention Pond #4 Conversion to Raingarden
Community Client/ Technical Advisor (s)	Horry County Government, Stormwater
Target Consumers/ Stakeholders	Horry County Government, Stormwater, Users of the Waccamaw River, Citizens in Horry County
Project Scenario & Context	When the Horry County Administration and Courthouse Building on 2nd Avenue and Laurel Street in Conway was constructed, large, dry stormwater detention ponds were built to control runoff from the parking lots and rooftops. These ponds, however, were not designed to address water quality. Horry County Stormwater has converted one of the dry detention ponds (Pond #3) into a large-scale rain garden to improve the quality of stormwater before it reaches the Waccamaw River. Some of the plants in the current retrofit have died out. The county wishes to convert a second pond (Pond #4) into a rain garden, implementing some of the lessons learned from the first intervention.
Problem Statement	Horry County and the users of the Waccamaw River need a stormwater management system that will collect rainfall runoff from the roofs and parking lots of the Horry County administration and courthouse building and must treat it before releasing it in less than 24 hours to the Waccamaw River. The current detention ponds were not designed for pollutant removal and allow untreated stormwater runoff to enter the Waccamaw River, which suffers from low dissolved oxygen and high bacterial levels during rain events and which is a drinking water source for the area.
Design Statement	Team Aqua-clina was tasked with proposing a design for a bioretention area that will utilize Pond #4 and limit ponding so that it does not generate mosquitoes and does not drown the plants. Standing water must drain from the rain garden in less than 24 hours. Selected plants must be able to survive the conditions in the bioretention area.

Table 9. Project #8: Bringing Green Back to the Coast

Project Title	Project #8: Bringing Green Back to the Coast
Community Client/ Technical Advisor (s)	Coastal Carolina University
Target Consumers/ Stakeholders	The Woods (at Coastal Carolina University) Student Housing’s Residents and Visitors
Project Scenario & Context	<p>The Woods Residence Halls were the first dorms on Coastal Carolina University’s campus. They were opened in 1987 by Chancellor Ronald G. Eaglin. The community comprises 6 buildings (3 stories each), which are named after trees predominantly grown in the South: Cypress, Dogwood, Elm, Maple, Oak, and Palmetto. The dorms are coeducational housing for new and first-year students with a total occupancy of about 420. The Woods buildings do not have their own laundry facilities, so students must travel to Eaglin and Ingle Halls to wash and dry their clothes. Conway receives, on average, about 55 inches of rainfall annually with a mean monthly low and high of 3.24 inches and 7.5 inches in March and August, respectively. There are frequent storms and hurricanes particularly during the fall semesters. The front areas of the dorm buildings consist of wetland slough with associated tree canopy (e.g., Laurel Oak, Bald Cypress) and are frequently flooded even during low-intensity rain events. Residents and visitors must trek through water puddles to get to and from classes or find alternate and indirect routes to their destinations on campus. According to the institution’s master plan, “the east-west ribbons of wetlands and associated woodlands remain and form a strong landscape character. These wetland areas should be preserved and enhanced: they play a key role in handling stormwater and they add a distinctive, authentic character and sense of place. . . . The University should build on the strong character of the spaces within Chanticleer Drive and improve the weaker courtyard spaces at the River residences and The Woods residences.” The Team will propose a low-impact development solution as part of the Environmental Protection Agency’s (EPA) Campus RainWorks Challenge— Green Instructure Design Competition.</p>
Problem Statement	Residents and visitors to the Woods Dorms at Coastal Carolina University have complained about flooding of the areas adjacent to and in front of the dorms. Students must trek through water and step over large puddles to get to and from their classes and laundry and cafeteria facilities. A bioretention system is needed to control stormwater runoff from the roofs and other pervious surfaces of the dorm while improving the weaker courtyard spaces.
Design Statement	The Team has been tasked with proposing a low-impact development solution to the flooding challenges at The Woods Residence Halls on the Coastal Carolina University campus. Per the criteria outlined in the EPA’s Campus RainWorks Challenge—Green Instructure Design Competition, the design area must cover no more than 15 acres, can be built within a reasonable time frame, and should offer one or more local stormwater management solutions that provide multiple environmental, economic, and social benefits.

NPDES Phase II—Integrating Community Engagement and Engineering Education

Table 10. Project #9: Lincolnshire Community Drainage Improvement Study & Design

Project Title	Project #9: Lincolnshire Community Drainage Improvement Study & Design
Community Client/ Technical Advisor (s)	Department of Public Works, Georgetown County
Target Consumers/ Stakeholders	Lincolnshire community members, SCDOT, SCDHEC & Georgetown County’s Department of Public Works
Project Scenario & Context	<p>The Lincolnshire Community is located approximately 2.5 miles west of the city of Georgetown, off Highway 521 (Highmarket Street) toward the city of Andrews. It is bounded by County Rd S-22-718 on the north, Whites Creek Rd on the east, Greentown Rd on the west, and Highway 521 or Highmarket Street on the south. The community encompasses approximately 60 acres of residential homes and secondary roads. Upon preliminary site inspection and review of the existing drainage system serving the community, it was determined that the entire community depends upon backyard drainage ditches to convey runoff from the roads and properties to the ultimate receiving water body—Whites Creek. The field reconnaissance determined that little or no maintenance (i.e., litter removal, grading, mowing) of the backyard ditches has been done. Therefore, there is no drainage connection from the community to the outfalls (outfalls close to Amelia Dr & Friendfield St and close to County Rd S-22-718 & Whites Creek Rd). Unfortunately, what little roadside drainage system exists is in bad condition, if working at all. This lack of maintenance has led to the deterioration of the roadbeds. Potholes and alligator cracking in roads are abundant. Standing water on the road and in roadside swales that are not connected to the backyard ditches is common as well, creating a mosquito nuisance.</p>
Problem Statement	<p>The residents of the Lincolnshire community in Georgetown, South Carolina, experience frequent flooding and property damage, even during 2-year storm events, and poor roads as a result of inadequate and/or failing and poorly maintained drainage systems. The community needs proper drainage as well as community empowerment, outreach, and educational programs to disincentivize littering; to prevent future floods and subsequent property damage, and to avoid further damage to roads and disease outbreak as a result of mosquito infestation.</p>
Design Statement	<p>CHK Engineering has been tasked with preparing a small drainage study of the Lincolnshire community, which includes development of a flow rate for the drainage area to design a ditch or pipe size for the downstream end (outfall) of the system. All assumptions with justifications must be stated. An attached Lincolnshire Drainage field inspection map is to be used to delineate the limits of the drainage area. Highway 521 should be considered the downstream end point, McDonald Rd is the northeast boundary, and Missroon St (County Rd S-22-685) is where the backyard properties may drain into as the northwest boundary. The GTC GIS contour layer must be used to determine this boundary and state their case. The Team must also prepare an innovative and creative educational and outreach program for litter control/removal for this specific community.</p>

DISCUSSION AND RECOMMENDATIONS

This project provided benefits both to the students and the community. The projects were linked to the course and program outcomes, thus extending the students' learning experiences beyond the classroom. Students' feedback on the course included:

- “enjoyed being able to have open discussion while working on real-world projects”;
- “great experience to be able to work within a group”;
- “I enjoyed using real-life situations and actually being able to solve a problem that involves our community. It made it more interesting for me and challenged me this semester. I broke a lot of barriers this semester by presenting frequently and doing lots of research”; and
- “project was very fun and gave a good insight to being an engineer. I enjoyed it thoroughly.”

About 50% of the students in the Engineering Program at Coastal Carolina University identify as underrepresented minorities. The ENGR 199/299 Cohort Grant Challenge Cornerstone Course Sequence is a curriculum requirement for all majors. These hands-on, experiential, community-based opportunities have been shown to be high-impact practices that broaden participation and increase retention in engineering programs. The initial partnership between the Engineering Program and CWSEC was very successful; it met and exceeded its objectives. Students learned about our planet's grand challenge of providing clean water, the impact stormwater has on the urban water cycle, and their abilities to contribute to solving this challenge using their engineering design skills. Additionally, students practiced meta-skills such as design, research, written and verbal communication, and client management. The next steps include: continue to engage consortium members and students on realistic, real-world problems; engage students on similar projects in other courses such as Senior Design; and facilitate more fieldwork when it is safe to do so. Additionally, formative and summative assessments of ABET student outcomes will be included in future studies.

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South Carolina Sampling, Analysis, and Governance of Per- and Polyfluoroalkyl Substances

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Abstract. The extent of sampling, analytical, and governance guidelines for per- and polyfluoroalkyl substances (PFAS) in individual states is currently inconsistent. There are no federally mandated regulations on PFAS, and the geochemical variations within different states can lead to regionally specific PFAS contamination, resulting in state-specific guidelines for PFAS contamination in different environmental matrices. There are no facilities in South Carolina known to currently or previously produce PFAS; however, they may be used in the production of other goods at industries throughout South Carolina, including Class B firefighting foams, consumer items, packaging, and stain- and weather-resistant fabrics. We assessed the sampling, analytical, and governance strategies of the South Carolina Department of Health and Environmental Control (SCDHEC) to understand current state-specific guidelines for PFAS contamination in South Carolina. This assessment indicates that SCDHEC has conducted sampling and analysis of community drinking water systems supplied by surface water for PFAS contamination. Additionally, risk indicators have been made for highly susceptible areas for likely PFAS contamination, including Department of Defense (DOD) and Department of Energy (DOE) sites, airports, and landfills in South Carolina. Recently, bills have been introduced into the South Carolina legislature to address PFAS. These proactive approaches in South Carolina aid in the assessment of the risks of PFAS contamination and are important steps for SCDHEC and South Carolina legislative stakeholders as they continue to develop and enforce state-specific standards for PFAS chemicals and await more information and official regulatory drivers from the US Environmental Protection Agency (US EPA).

INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a group of between 5,000 and 10,000 humanmade, fluorinated, organic chemicals that have been manufactured and used in various industries around the world (ITRC 2020; 3M 2020; Dorrance et al. 2017). PFAS have a unique combination of chemical properties, which result in benefits such as low surface tension, oil-repellent ability, and water solubility. These properties enable their use in applications including biocides, hydraulic fluids, firefighting foam, and household products (Rayne and Forest 2009; Kim et al. 2015; Ahrens et al. 2009). Their widespread use has led to their detection in food, commercial household products, workplaces, drinking water, and living organisms (Domingo and Nadal 2017; Kucharzyk et al. 2017; Rahman et al. 2014; Valsecchi et al. 2013). PFAS have been coined as “forever chemicals” due to the extremely strong carbon-fluorine bond. Because of their persistence in the environment and human body, as well as

a lack of understanding the full health risks associated with exposure, PFAS are emerging contaminants of concern.

When assessing the hazards of chemicals, many states rely on guidance from federal agencies to sample, analyze, and regulate these chemicals. For PFAS, the US Environmental Protection Agency (US EPA) has developed sampling and analytical methods for 29 PFAS analytes in drinking water (US EPA 2020a). Aside from this, only nonenforced federal guidelines currently exist for PFAS, like the EPA PFAS Action Plan, which recommends the lifetime health advisory of 70 ppt for perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) combined. As a result, states like South Carolina (SC) have begun testing for PFAS (SCDHEC, 2020).

Due to the growing body of science and literature around PFAS, combined with public pressure on legislative bodies to regulate PFAS, it is important to understand what South Carolina is doing to ensure that its residents are safe from PFAS contamination as well as how the Department of Energy (DOE) and Department of Defense (DOD) are

involved. The goals of this paper are to analyze SCDHEC data and reports on PFAS chemicals and (1) identify major locations of PFAS contamination and highly susceptible locations for PFAS contamination in South Carolina, (2) identify the PFAS sampling and guidance procedures used by South Carolina, and (3) be aware and knowledgeable of current and impending PFAS regulations in South Carolina.

MATERIALS AND METHODS

PFAS information for South Carolina was collected by searching through the South Carolina Department of Health and Environmental Control (SCDHEC) website. The information found through the SCDHEC website was stored on a secure database. For information or data on PFAS sampling, analyses, or regulations that were missing or unavailable online, an email was sent to a point-of-contact within the SCDHEC, and the information was retrieved via email or telephone.

RESULTS AND DISCUSSION

VULNERABLE SITES FOR PFAS CONTAMINATION IN SOUTH CAROLINA

The SCDHEC Bureau of Water (BOW) released a report detailing the internal strategy to assess PFAS in drinking water (SCDHEC 2020). This report identified sites throughout the state where PFAS contamination was plausible and the existence of an associated risk based on the three most significant vulnerability factors: (1) PFAS source type, (2) drinking water source, and (3) groundwater aquifer system type based on peer-reviewed literature (Table 1).

Department of Defense and Department of Energy Sites

The most concerning sites for PFAS contamination in South Carolina are DOD facilities due to the potential usage of aqueous film forming foam (AFFF), the PFAS-containing military grade fire retardants, since 2014 (DOD 2018). The DOD and DOE are investigating PFAS as an emerging contaminant under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as it may endanger public health and the environment. The DOD is actively investigating its military installations in South Carolina through their PFAS Task Force (DOD, 2020), and the DOE is investigating its Savannah River Site (SRS) for potential PFAS contamination at the request of the SCDHEC (2020). The SCDHEC’s Bureau of Land and Waste Management (BLWM) is actively working with the DOD on their investigation of the eleven South Carolina military installations (Figure 1), including the stakeholder review process.

Table 1. Number of Sites in South Carolina Identified as Plausible PFAS Locations with Associated Risk

Risk Ranking	Source Types	Number of Sites in South Carolina
1	DOD/DOE	11 DOD/1 DOE
2	PFAS or FP Manufacturing	0
3	Landfills	677
4	Part 139 Airports	8
5	Fire Training Areas	2+
6	Petroleum Refineries	0
7	Industrial	384
8	Wastewater Treatment Plants	746

South Carolina Regional and International Airports

Regional and international airports that serve scheduled and unscheduled flights with more than 30 passenger seats, serve scheduled air carrier operations in aircraft between 9 and 31 seats, and the Federal Aviation Administration (FAA) Administrator requires to have a certificate must be certified as a Part 139 airport. This certification requires the airport to have aircraft rescue and firefighting (ARFF) capabilities, which includes proper equipment (e.g., AFFF), personnel, and training. Under the FAA, Part 139 airports are required to conduct an annual timed drill for firefighting response using AFFF (FAA 2020). South Carolina houses 8 Part 139 airports (Figure 1) that have potentially performed annual fire drills with AFFF discharges (SCDHEC 2020).

South Carolina Fire Training Areas

In addition to DOD installations and Part 139 airports, fire training areas are those where the discharge of AFFF could have occurred. The BOW lists at least 500 fire stations in South Carolina with unknown usage of AFFF (SCDHEC 2020), but two areas are of high concern. Columbia, South Carolina, is home to a very large and extensive fire training facility in the US. The South Carolina Fire Academy Facility encompasses 208 acres north of Columbia and is known to have trained with AFFF. The Fire Academy was previously located at the Columbia Metropolitan Airport, and both locations are likely to have legacy PFAS concentrations from AFFF usage (SCDHEC 2020).

South Carolina Landfills

Landfills and their associated leachates are areas of potential PFAS contamination concern because historically PFAS were used in nonstick and weatherproofing applications, as well

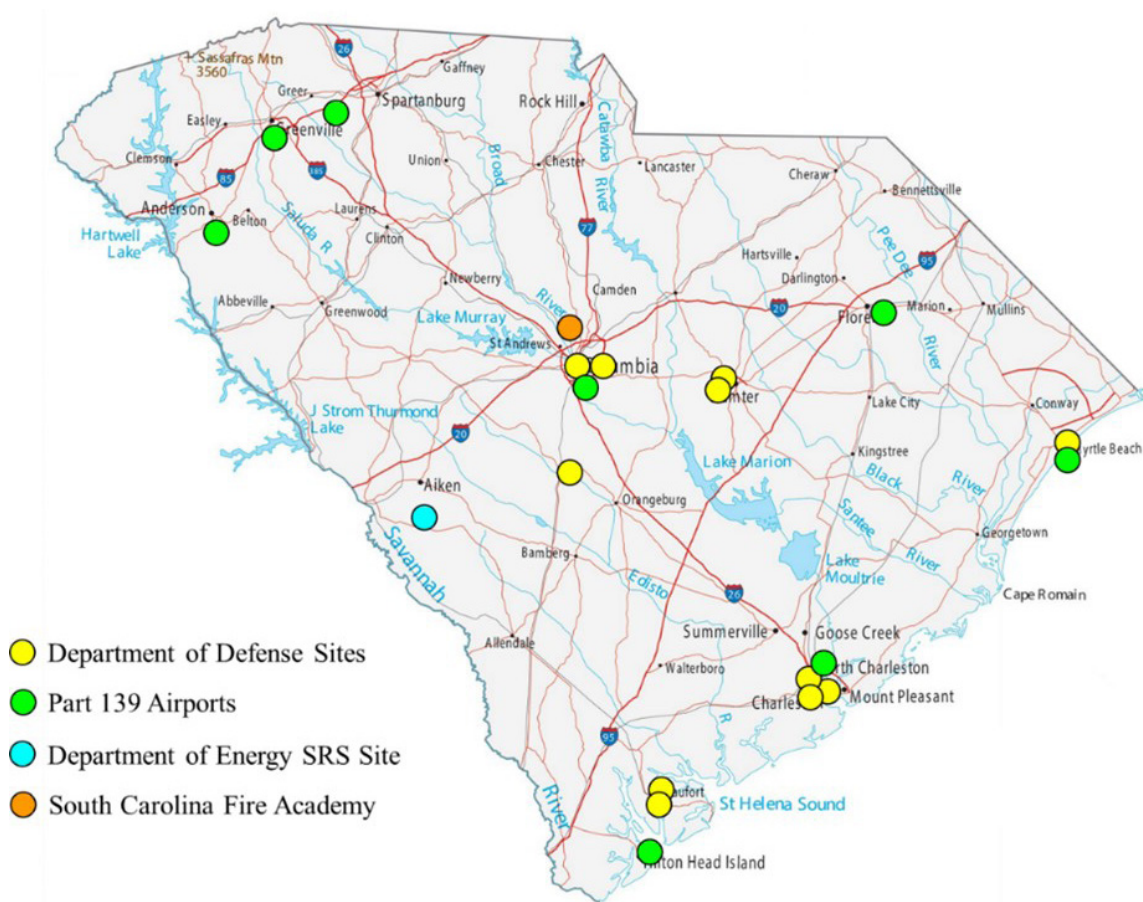


Figure 1. Vulnerable locations for PFAS contamination in South Carolina. The 500+ fire stations in South Carolina with unknown AFFF usage are not included in the map.

as food packaging, that have been discarded. South Carolina has 677 total landfills comprised of Class 2 (construction and demolition debris), Class 3 (municipal solid waste, construction, demolition, and industrial solid waste), and industrial-only landfills. Active landfills (N=107) can accept municipal solid waste, debris, and industrial solid waste, while inactive (N=570) landfills either are not operational or are operational but have not accepted waste since 1940. Active landfills are of most concern for PFAS because these chemicals do not degrade over time and may leach out of the landfills (i.e., landfill leachate). Figure 2 highlights the locations of current active Class 2 and Class 3 landfills in South Carolina that are susceptible to PFAS contamination (SCDHEC 2020).

Other Vulnerable Sites in South Carolina

The SCDHEC BOW has identified high-risk industrial facilities and has grouped them into the following: (1) organic chemicals, plastics, and synthetic fibers; (2) pulp and paper; (3) textiles; and (4) airports/other. South Carolina is home to 65 organic chemicals, plastics, and synthetic fiber facilities; 11 pulp and paper facilities; 68 textile facilities; and 240 airports or other potential locations (SCDHEC, 2020). Wastewater

treatment plants are locations ideal to be investigated due to the acceptance of industrial waste. There are 746 wastewater treatment plants in South Carolina: 146 domestic facilities, 90 municipal facilities (with pretreatment), 126 municipal facilities (without pretreatment), and 362 individually permitted facilities (SCDHEC 2020).

SOUTH CAROLINA PFAS SAMPLING AND ANALYSIS

There has been a varied response by states with respect to PFAS sampling requirements. Of the 50 US states, 22 are not actively sampling, and the remaining 38 are sampling in one type of environmental matrix as of July 2021 (ITRC 2021). All states that have reported sampling efforts monitor drinking water using standards recommended by either the US EPA or the Interstate Technology and Regulatory Council (ITRC 2020). Out of the 38 states, 12 report sampling groundwater, while only 9 are sampling surface water.

South Carolina has sampled and analyzed for PFAS in community drinking water systems where raw water is supplied by surface waters using US EPA methods 533 and 537.1 [US EPA 2020a). These standard US EPA methods provide information on sampling methods, including the correct equipment to use when sampling, the method for

sampling, information on decontaminating equipment after sampling, information on collecting and handling samples, and shipping samples for PFAS drinking water samples. The SCDHEC has sampled for PFAS in 44 community drinking water systems, while 10 other community drinking water systems have provided data to the SCDHEC on sampling and analysis results. Trends and observations of compliance sampling performed by the SCDHEC are shown in Table 2 (SCDHEC 2020). However, it is important to note that the US EPA method 537.1 has method detection limits for individual compounds between 10 and 90 parts per trillion (ppt), and more sensitive methods are now available. The method detection limits from this method can be presumed insufficient to meet reporting guidelines for health advisory levels established by PFAS guidance documents in states that have developed their own PFAS sampling and analytical guidelines.

This sampling effort has accounted for approximately 3.3 million of the approximate 4 million users (82%) of community water systems in South Carolina (see Table 2). Current efforts include the SCDHEC sampling of community drinking water systems supplied by groundwater, and the SCDHEC BOW workgroup is developing strategies to

assess PFAS contamination in ambient surface waters and groundwater, including fish tissue (SCDEC 2020). Peer-reviewed literature has found PFAS in sediments and wildlife tissues previously (Fair et al. 2019; Tipton et al 2019; White et al. 2015). In addition to PFAS testing by the SCDHEC, the company Corix Utilities, which is a parent company of Blue Granite Water Company of South Carolina, is planning regular testing for PFAS at 365 of its water systems across the country, even though the US federal government doesn't require routine testing (Fretwell 2020).

SOUTH CAROLINA CURRENT AND IMPENDING PFAS REGULATIONS

The US EPA has set a lifetime health advisory for PFOA and PFOS in the amount of 70 parts per trillion (ppt) combined. A health advisory provides information on contaminants that are known or suspected to have adverse health effects on people. These are nonenforceable and nonregulatory but provide information to states agencies and public health officials on information spanning from health effects, analytical methods, treatment options, and so forth associated with drinking water contamination. This is used to be a buffer or offer a margin of protection to protect all

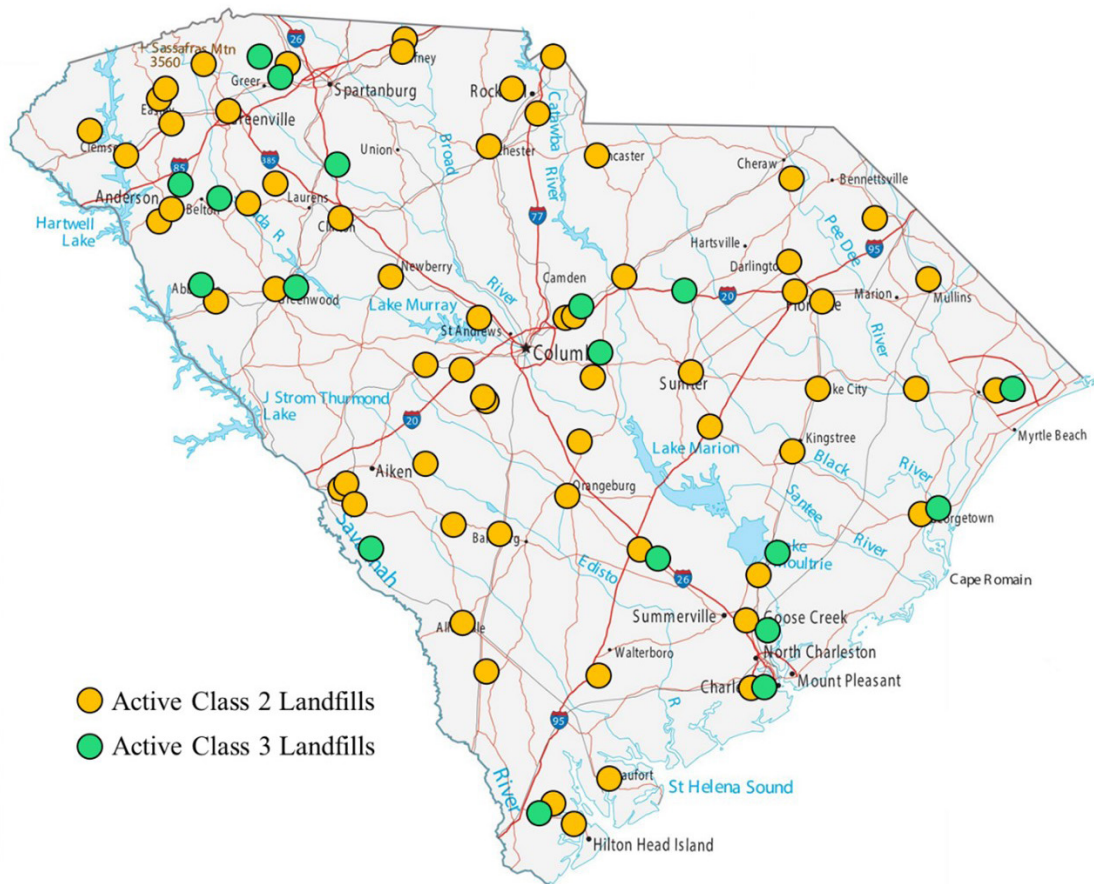


Figure 2. Active Class 2 and Class 3 landfills in South Carolina that are vulnerable to PFAS contamination.

Table 2. Summary of Findings from SCDHEC Sampling of Public Water Systems (SCDHEC, 2020)

Observation	Result
Community Drinking Water Systems Sampled by SCDHEC	44
Community Drinking Water Systems that Provided Data to SCDHEC	10
Population Served of Sampled Water Systems	82%
Number of Exceedances of EPA's LHA of 70 ppt	0
Maximum PFOA Concentration Measured	18 ppt
Maximum PFOS Concentration Measured	16 ppt
Maximum Combined PFOA and PFOS Measured	32 ppt

Americans from adverse health effects from unregulated contaminant exposure. In the US EPA's 2020 PFAS Action Plan, the main focus of their PFAS drinking water goals are to move forward with the establishment of a maximum contaminant level for PFOA and PFOS under the Safe Drinking Water Act (SDWA) (US EPA 2020b). A part of the SDWA established in 1974 is the Unregulated Contaminant Monitoring Rule (UCMR), which began in 1999 and which cycles through a maximum of 30 unregulated contaminants. Every 5 years, the list of contaminants is updated, and they are monitored throughout the country in public water systems serving more than 10,000 people (US EPA 2020b). Under UCMR 3, the SCDHEC tested for applicable PFAS at all public water systems fitting the monitoring criteria. Additionally, small sites serving under 10,000 people were randomly tested (SCDHEC 2020).

As noted earlier, there is a mixed response by states in monitoring requirements for PFAS. The US EPA (2020b) put out an action plan addressing strategies and potential regulatory decisions. The SCDHEC has complied with federal requirements, such as sampling public water systems, but has decided that more scientific information is required before recommending regulations to be passed on a state level. South Carolina is following the US EPA's Health Advisory Bulletin until such time as either state or federal regulations are enacted (SCDHEC 2020). The SCDHEC will remain involved and up to date regarding national regulatory progress (SCDHEC 2020).

The regulation of PFAS chemicals at both the state and federal levels is ever changing. As new information surrounding PFAS emerges, guidance documents and legislation become outdated quickly. This is evident in South Carolina, where new and amended bills continue to be introduced into the South Carolina legislature. Bill 4718 was introduced in January 2020. This bill was added to amend pending Bill 5339 (Cancer Prevention Act) by adding a section to require the SCDHEC to promulgate regulations to establish MCLs for certain pollutants, specifically PFOA, PFOS, other PFAS, hexavalent chromium, 1,4 dioxane, and other contaminants where regulations have been established in 2 or more states. It

is required that decisions be made based on studies, peer-reviewed science, information from the Agency for Toxic Substances and Disease Registry (ATSDR), and evidence from other states. Additionally, new House Bill H.3515 was introduced in the current session and is in committee following a joint resolution in both the State House and Senate. Bills 5339 and 4718 have been introduced to the SC House and are in committee. To be passed, the bills are required to be passed by both the SC House and the SC Senate, ratified, and approved or vetoed by the governor (SC State Government 2020).

CONCLUSIONS

Currently, the assessments made by the SCDHEC are most concerned with protecting the public from exposure to PFAS contamination. The focus of sampling has been on drinking waters provided to South Carolina residents, with less focus on the assessment of PFAS-contaminated sources. Due to the lack of case-specific information about PFAS use or disposal at given sites within South Carolina, the necessity for a standard method that can be used for vulnerable sites within the state becomes apparent. Other states, like Michigan, California, and New York, have developed and made public state-specific sampling and testing guidelines for PFAS chemicals in a multitude of environmental matrices (Michigan 2021; California 2021; New York 2021). It is imperative that the SCDHEC (a) remains vigilant in gathering new data of PFAS contamination as new or updated information is presented; (b) communicates information with stakeholders and the public in a timely, consistent, and transparent fashion; and (c) extends sampling and analytical efforts to other environmental matrices for a variety of PFAS analytes once methods and specific guidelines are available.

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Identification of Stormwater Pollution Hotspots in Charleston Peninsula

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Abstract. Flooding is of great concern in fast-growing coastal communities, especially in the southeastern US, due to multiplying threats such as extreme precipitation, coastal storms, and rising sea levels. Contamination associated with stormwater runoff is often given less attention during stormwater planning and management decisions. The US EPA has long recognized that stormwater runoff is the biggest contributor to the impairment of water bodies in the US. In this study, we studied stormwater runoff contamination in a densely developed section of downtown Charleston, South Carolina, to better understand the extent of the problem and identify potential hotspots that could aid in future stormwater management decisions. We focused on a 4.25 km² section of peninsular Charleston that has a dense mix of residential, commercial, and industrial land use. High-resolution 2.5-m elevation data was used to subdivide the research area resulting in four distinctive subwatersheds, each of which had a distinctive land-use pattern. For 16 months starting in September 2016, stormwater samples were collected near storm drains at 24 sites distributed within the 4 subwatersheds immediately after large rainfall events. These water samples were analyzed for enterococci (a fecal indicator bacteria), trace metals (As, Cd, Cr, Cu, Pb, Ni, V, and Zn), and nutrient (NO_3^- and PO_4^{3-}) concentrations. Our data indicated that enterococci concentrations were extremely high in the entire watershed and that these concentrations tended to be higher on days where there was antecedent rain preceding the sample collection. These concentrations were also higher during warmer times of the year (July–September). Trace metals were detected in all filtered water samples, and these concentrations positively correlated with traffic patterns and hence were more prevalent in areas of high traffic. Nutrient ions were present in all water samples, while the PO_4^{3-} concentrations exceeded US EPA ecological standards; PO_4^{3-} concentrations were highest in the subwatershed with the highest residential land use. By coupling these stormwater quality data to watershed delineation, weather conditions, and land-use patterns, we were able to identify general hotspots for stormwater contaminants. The data suggest that there would be public health concerns in areas that are disproportionately affected by stormwater flooding. These insights into the myriad ways natural water systems in fragile coastal ecosystems are being impaired can be employed in stormwater management. We recommend that government agencies include stormwater quality concerns in future planning.

INTRODUCTION

The US Census Bureau reported that between the years 1960 and 2008, the US population grew fastest along the Atlantic, the Pacific, and the Gulf of Mexico shorelines compared with the rest of the country (Wilson and Fischetti 2010). In the most recent decade (2010–2019), population growth was higher in nearly all of South Carolina's coastal counties when compared with overall South Carolina (<https://www.census.gov/quickfacts/fact/table/US/PST045219>). Similar higher population growth has been reported (at least 17.5% growth in the most recent decade compared with 6.3% growth across the US) in the densely populated coastal counties of Berkeley,

Charleston, and Dorchester. These counties currently have a significantly higher population density compared with the state of South Carolina and a much higher urban footprint as well. The coastal watershed in this region, which includes the City of Charleston, spans Berkeley, Charleston, and Dorchester (BCD) counties and is part of the Santee River Basin (Hughes et al. 2000). Recent forecasts predicted that urbanization around Charleston, South Carolina, will triple by 2030, as the most common form of land-use change is caused by urban expansion (Allen and Lu 2003; Drummond et al. 2015). The US National Climate Assessment indicates that extreme precipitation along with rapid sea-level rise will have a significant impact on coastal South Carolina over

the next several decades (NOAA 2017). Water quality in the coastal water of this region is also expected to severely degrade as a result of this growth (Allen and Lu 2003). Increased impervious surfaces increase stormwater runoff volume and are linked to habitat degradation from channel erosion and higher pollutant loads (Aryal et al. 2010; Beckingham et al. 2019; Exum et al. 2005). Nonpoint source pollution associated with stormwater runoff is already the most significant cause of surface water impairment in the US (Exum et al. 2005). The most common pollutants include trace metals, polycyclic aromatic hydrocarbons, pathogens, and nutrients (Aryal et al. 2010; Exum et al. 2005).

Microorganisms that are commonly associated with the gut of animals, such as enterococci and *Escherichia coli* (or *E. coli*), are commonly used as indicators for the presence of fecal pathogens in natural water bodies and runoff and thus are referred to as fecal indicator bacteria (FIB) (Selvakumar and Borst 2004). Failing sewage systems, or pet and wild animal waste, are major contributors to the concentration of FIB in stormwater runoff. There is a significant positive correlation between the presence of FIB and urbanization of land upstream of an open water body when compared to undeveloped land (Van Dolah et al. 2008).

Trace metals are commonly present in the urban environment and are especially concentrated in urban/industrial areas due to brake and tire wear, vehicle exhaust, and industrial activities (Aryal et al. 2010). Trace metals such as As may be present because of natural sources such as weathering of phosphate rocks (Sanger et al. 1999). Trace metals often accumulate in road dust either directly or as a result of atmospheric deposition during dry periods and either dissolve in runoff or are sorbed to suspended sediments (Ma et al. 2016). Nutrient contamination is also widely present in urban watershed runoff; in particular, nitrogen and phosphorus in the form of NO_3^- and PO_4^{3-} contributes to the eutrophication of water bodies. There are additional sources of contamination in use and human/animal waste (Aryal et al. 2010).

Stormwater in the coastal urban watershed ultimately discharges into the estuaries causing degradation of coastal water quality. The Charleston Harbor estuary, which includes the Ashley, Cooper, and Wando Rivers, is considered dissolved oxygen-impaired by the US EPA and the SCDHEC (Cantrell 2013). Other studies in the region confirm impairment in other forms as well, including benthic sediment (Sanger et al. 1999), estuarine habitat (Van Dolah et al. 2008), and shellfish, fish, and mammals (Baechler et al. 2020; Fair et al. 2019; Houde et al. 2005). Stormwater runoff has the most significant impact on all coastal environments but is extremely hard to manage due to the diffuse nature of the pollution.

The main goal of this study was to analyze stormwater quality and identify stormwater contamination hotspots in

an urban watershed. The study area is the highly developed urban watershed in the historic downtown section of the city of Charleston, South Carolina. Based on the literature review and our preliminary studies, we hypothesized that the stormwater runoff in the city will be contaminated and will reflect the predominant land-use characteristic of a given section of the watershed. To test this hypothesis, we collected stormwater samples in a broad section of Charleston peninsula, which we subdivided into four sections based on the predominant flow direction of the stormwater runoff. In each of these sections (subwatersheds), we collected discrete stormwater samples during significant rain events that generated sheetflow and runoff between September 2016 and January 2018. By combining water quality with the spatial and statistical analysis, we determined significant hotspots for different sets of contaminants and potential sources of contamination. This approach can be useful in understanding the factors involved in urban stormwater contamination as well as in its subsequent management. The general approach or framework can be adapted to other settings.

MATERIALS AND METHOD

SITE DESCRIPTION

The City of Charleston, South Carolina, is located within the Southeastern Atlantic Lower Coastal Plain (Figure 1). The land area is approximately 290 km², of which the historic peninsula makes up approximately 21 km². The natural, unaltered watershed in this region is forested and characterized by a low topographical gradient and shallow water table (Griffin et al. 2014). The Charleston peninsula has undergone significant land-use change since its founding, and since then many changes were made to the natural depressions, wetlands, and salt marshes by draining and/or filling these areas (Butler 2020). In the decades since 1970, rapid population growth in the region has resulted in an acceleration of land-use change across the region (Allen and Lu 2003; Beckingham et al. 2019).

The average temperature in this region ranges from 9.89 °C in the winter to 28.2 °C in the summer, and the average annual precipitation is approximately 1128 mm yr⁻¹ (<https://www.weather.gov/chs/climate>.) This area receives approximately 41% of its rain during the summer months, which includes a high number of thunderstorms or short, intense storms that contribute to spikes in surface runoff (BCDCOG 2011). More recently, fair weather or sunny day flooding caused by King Tides and rising sea levels have occurred with greater regularity and frequency, causing additional pollution loading and discharges into estuarine waterways (Harris and Ellis 2021; Román-Rivera and Ellis 2018). The Charleston peninsula (Figure 1) is part of the South Carolina Department of Health and Environmental Control's (SCDHEC's) Cooper River Basin (includes EPA

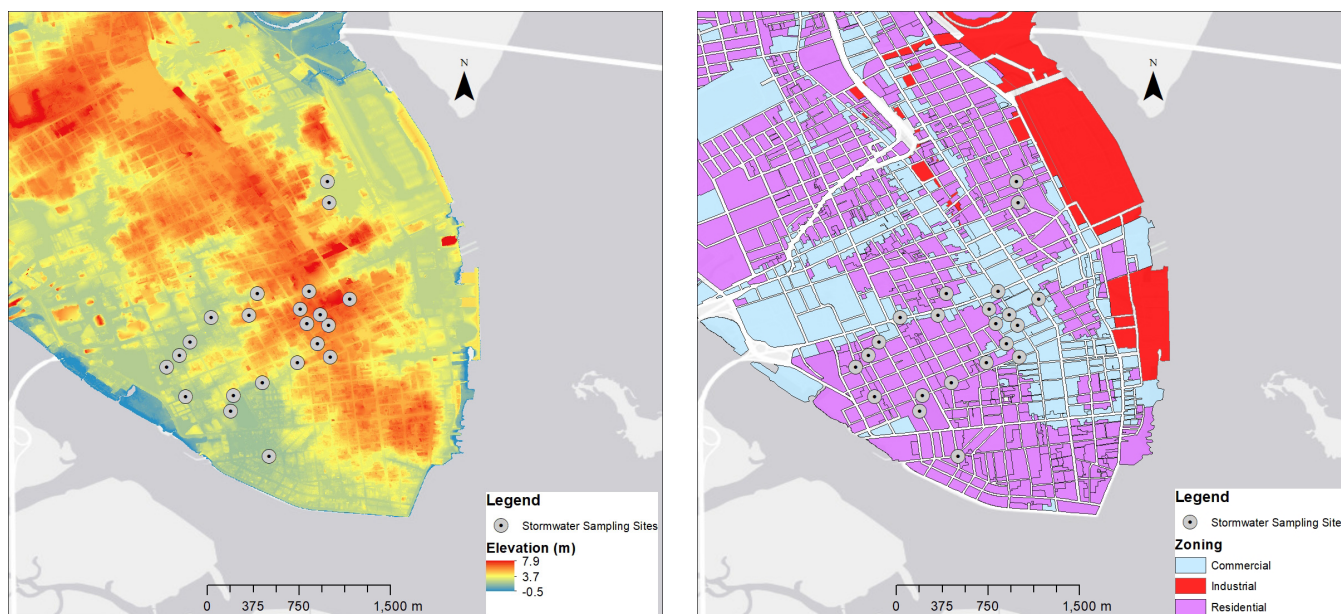


Figure 1. Elevation (left) and land-use (right) patterns of the Charleston peninsula. Stormwater sampling locations are also shown. Sites were chosen at accessible storm drains. Not all sites were sampled during every rain event. Map data sources: USGS, SC DNR, and the city of Charleston

hydrologic units 03050201 and 03050202) and includes parts of the Charleston Harbor and the Cooper, Ashley, and Wando Rivers.

In relatively unaltered environments of this region, the surface soils ranging from sandy-to-loamy types and the subsurface soils ranging from loamy-to-clayey types locally influence natural infiltration and runoff patterns (Griffin et al. 2014). There is very minimal overland flow following rainfall—rainfall usually infiltrates the ground surface, causing the water table to rise and thereby increasing contribution to the baseflow component of stream discharge (Griffin et al. 2014). Natural drainage occurs in broad areas of swamps, wetlands, and tidal marshes. The system is dominated by high tidal amplitudes; because of its low elevation, the broad region is considered estuarine (Houde et al. 2005; Van Dolah et al. 2008). The soils on the Charleston peninsula are classified as UR (Urban land-Yauhannah-Yemassee-Ogeechee association) or urban soil by the USDA-NRCS (<http://websoilsurvey.nrcs.usda.gov/>). These soils include fill material and have indeterminate soil physical and chemical properties. Because of the high amount of impervious surfaces, the land on the Charleston peninsula has a higher amount of surface runoff compared with unaltered environments (Blair et al. 2014)

STORMWATER SAMPLING

Stormwater samples were collected from an area of approximately 4.25 km² of an urban downtown area of the city of Charleston. This area was subdivided into four

subwatersheds (Calhoun, Harbor, Colonial, Tradd; see Figure 1) based on watershed delineation, as described in the next section. Between September 2016 and July 2017, 10 rain events were monitored, and stormwater grab samples were collected from multiple sites. For each of the 4 subwatersheds, we canvassed and identified a minimum of 4 sampling sites (Figure 1). The site locations were local topographic low points, where significant stormwater flow into curbside storm drains was observed. In total, 23 sites were sampled during 10 rain events (which are defined as precipitation heavy enough to generate runoff—approximately 1 cm), although not every site was sampled during every rain event. Precipitation data were obtained from NOAA's National Weather Service (NWS) website for downtown Charleston (<https://www.weather.gov/chs/climate>). The data included the cumulative 3-day precipitation period before the sampling day (antecedent precipitation), as well as the cumulative 24-hour period on the sampling day.

Sampling procedures were adapted from the US EPA standard methods (US EPA 2009). In all cases, stormwater runoff depth near curbside storm drains was deep enough that grab sampling was feasible. Grab samples were collected directly into clean and sterile sample containers, carefully avoiding contact between the road and the sample container without disturbing the sediment at bottom of the water column. Two types of grab samples were collected: (1) samples for fecal indicator bacteria (FIB) analyses and (2) samples for chemical analyses. The first type of samples was collected in 120 mL sterile bottles containing sodium thiosulfate preservative

Identification of Stormwater Pollution Hotspots in Charleston Peninsular

(IDEXX Laboratories Inc.). These samples were immediately stored in a plastic cooler and prepared for FIB analysis within 6 hours of sampling, as described in the following section. The second type of samples was collected in 50 mL clean, sterile plastic centrifuge tubes (FisherBrand, Thermo Fisher Scientific Inc.) and prepped for chemical analyses, as described in the following section. In all cases, samples and bottles were handled with appropriate personal protective equipment. When needed, water samples were filtered using 0.22 μm polyethersulfone (PES) syringe filters (Millex-GP, Millipore Sigma, Burlington, MA) or diluted using sterile or nonsterile 18.2 M Ω .cm resistivity deionized water.

DELINEATING SUBWATERSHEDS

To identify predominant sheetflow and natural drainage patterns, approximately 4.25 km² (Figure 1) of peninsular Charleston was divided into subwatersheds. Preliminary data were obtained from the city of Charleston's Master Floodplain Analysis (Davis & Floyd Inc. 1984) and were coupled with a 2.5-m resolution elevation (Digital Elevation Model, or DEM) lidar dataset (from the South Carolina Department of Natural Resources, <http://www.dnr.sc.gov/GIS/lidar.html>.) Note that bald earth corrections were not applied to the lidar data to allow the human infrastructure (e.g., building structures) to influence stormwater drainage. The delineation of watersheds used ground surface elevation data to identify the boundary (watershed divide) of an upslope area that contributed to a concentrated outlet or a drain. Typically, contour maps can be used to determine the watershed boundaries (NRCS 1991); however, this method is not very reliable in low-gradient watersheds. In this study, we used the built-in Hydrology toolset of ArcGIS software (ArcGIS Desktop, Esri) for basin delineation (Moore et al. 1991). The 2.5-m resolution DEM data within the area of interest was broken into small grids (2.5 m \times 2.5 m) or "cells" whose elevation is known. The Hydrology toolset assumes that there is water present in all cells and identifies the flow direction of water between adjoining cells using the following constraints: (1) flow occurs from higher to lower elevations; (2) when multiple adjacent cells have elevation gradients, flow occurs preferentially toward cells that have steeper gradients; (3) flow accumulates in any cell as water flows from a higher to a lower elevation cell, and (4) flow only occurs when there is a difference in elevations or flow does not occur. The flow direction and accumulation direction identify the streams (and stream orders) that form within a basin, while the no-flow areas help identify the basin boundary. Once the ArcGIS-Hydrology toolset finished the analysis, the locations where water was likely to exit the sample area were identified by analyzing the connected flow paths in the flow direction. Subwatersheds were then delineated with the flow direction raster, using known outfall locations from the city of Charleston's published stormwater sewer network ([\[data-charleston-sc.opendata.arcgis.com/\]\(https://data-charleston-sc.opendata.arcgis.com/\)\) as pour points \(outlets\). Basin boundaries generally follow high-elevation ridgelines. The Hydrology toolset does not include storm sewers and does not accurately represent subsurface drainage and urban flow networks, so our subwatersheds reflect only overland flow in the study area.](https://</p></div><div data-bbox=)

WATER ANALYSIS

To quantify FIB concentrations in water, enterococci bacteria were measured using a standard fluorogenic substrate enterococcus test (Enterolert, IDEXX Laboratories Inc.) (APHA-AWWA-WEF 2017; ASTM 2019). Stormwater samples collected in sterile bottles were diluted 100 times using sterilized deionized water (18 M Ω .cm). Then, a nutrient indicator reagent is added to the sample, mixed thoroughly, and poured into a 96-well Quanti-Tray/2000 (IDEXX) tray, thermally sealed, and incubated for 24 h at 41.0 \pm 0.5 $^{\circ}\text{C}$. All wells that are positive for enterococci bacteria fluoresce under UV light and are quantified using a most probable number (MPN) table to obtain an MPN for each sample. The dilution factors were applied to the final MPN values and were expressed as MPN per 100 mL of stormwater. Both positive controls (*E. faecalis*) and blank samples were incorporated during each week's analyses. These analyses were performed in an SCDHEC-certified lab and were overseen by the lab director and staff.

Dissolved trace metals (As, Cd, Cr, Cu, Pb, Ni, V, and Zn) in water were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7500cx). All stormwater samples were filtered as described previously and acidified to 2% v/v acidity using HNO₃ (Optima grade, Thermo Fisher Scientific, Inc.). A multi-element standard mix (High Purity Standards) was used to calibrate the ICP-MS. All samples and standards were spiked with 1 $\mu\text{g L}^{-1}$ of Rh and Au internal standards. To account for instrument bias, the mass count ratios of each analyte and an appropriate internal standard were used for quantification. Check standards and blanks (2% v/v HNO₃ in deionized water) were incorporated during analyses of each batch of samples. The linear analytical range for all elements was 10⁻⁴-10 mg L⁻¹ and the method detection limit was lower than 10⁻⁴-10 mg L⁻¹. In all cases, triplicate measurements for each element were less than 5% relative standard deviation (RSD).

An ion chromatograph (IC, Thermo Dionex ICS-5000+, Thermo Fisher Scientific, Inc.) with a conductivity detector, a microbore isocratic pump, and an electrolytic suppressor was used to measure NO₃⁻ and PO₄³⁻ concentrations in water samples. An anion exchange column (Thermo IonPac AS22 2 \times 250 mm) paired with 2 guard columns (Thermo IonPac AG22 2 \times 50 mm and Thermo IonPac NG1 2 \times 50 mm) and a 4.5 mM sodium carbonate and 2.0 mM sodium bicarbonate eluent prepared using deionized water (18 M Ω .cm) was used for the ion separations. A 50- μL sample was injected and

separated at 0.4 mL min^{-1} for a total elution time of 12 min. A multi-anion standards mix (High Purity Standards) was used to calibrate the peak areas. Laboratory blanks (deionized water) and check standards were incorporated in each batch of samples. A linear analytical detection range of $1\text{-}50 \text{ mg L}^{-1}$ was obtained with a $\pm 5\%$ RSD for the check standards. Duplicate measurements for samples yielded concentrations within a 5% range, indicating stability of the instrument and the peak integration routines.

STATISTICAL ANALYSES

Due to the large number of analytical variables (dimensions or correlated variables) within the study (e.g., sites, solute types, concentrations, precipitation, locations, sample size), we used principal component analysis (PCA) to reduce the large set of dimensions into a smaller number of dimensions that collectively explain most of the variability in the original set (Christophersen and Hooper 1992; Hair et al. 1998). This method is especially useful in identifying relationships between different variables. An $n \times p$ data matrix (where n is the number of observations and p is the type of observation or the dimensions) was reduced into a lower dimension or principal component space while capturing a good representation of all variability. The first principal component (PC1) is a normalized linear combination of the observations that has the largest variance. Subsequent principal components (PC2, etc.) are normalized linear combinations of observations that are uncorrelated with previous principal components (PC1,

etc.) The general expectation was that the first few principal components will account for substantial variation within the data. PCA biplots between PC1 and PC2 were used to project all data as coordinate points, and each type of observation was plotted as a vector pointing toward the direction that represents the maximum correlation between the variable and the principal components. All raw data was scaled so that each of the variables had a mean of 0 and a standard deviation (variance) of 1. A covariance matrix was created for the scaled variables, followed by the calculation of eigenvalues of the covariance matrix. The eigenvector that corresponds to the largest eigenvalue is PC1, and so on. Strong correlations were depicted by the length of the vector. Vectors that were oriented in the same direction (acute angles) indicated that observations were correlated, while inversely correlated variables were oriented in opposite directions (or obtuse angles). Open-source software R (<https://www.r-project.org>) was used for all statistical computations.

RESULTS

WATERSHED DELINEATION

The four subwatersheds identified were named for the major streets or historical landmarks within each subwatershed (Figure 2). Within each subwatershed, runoff drains into a unique area: the Charleston Marina, the mouth of the Ashley River (seaward of the marina), the Cooper River, or Colonial Lake. The corresponding subwatersheds are

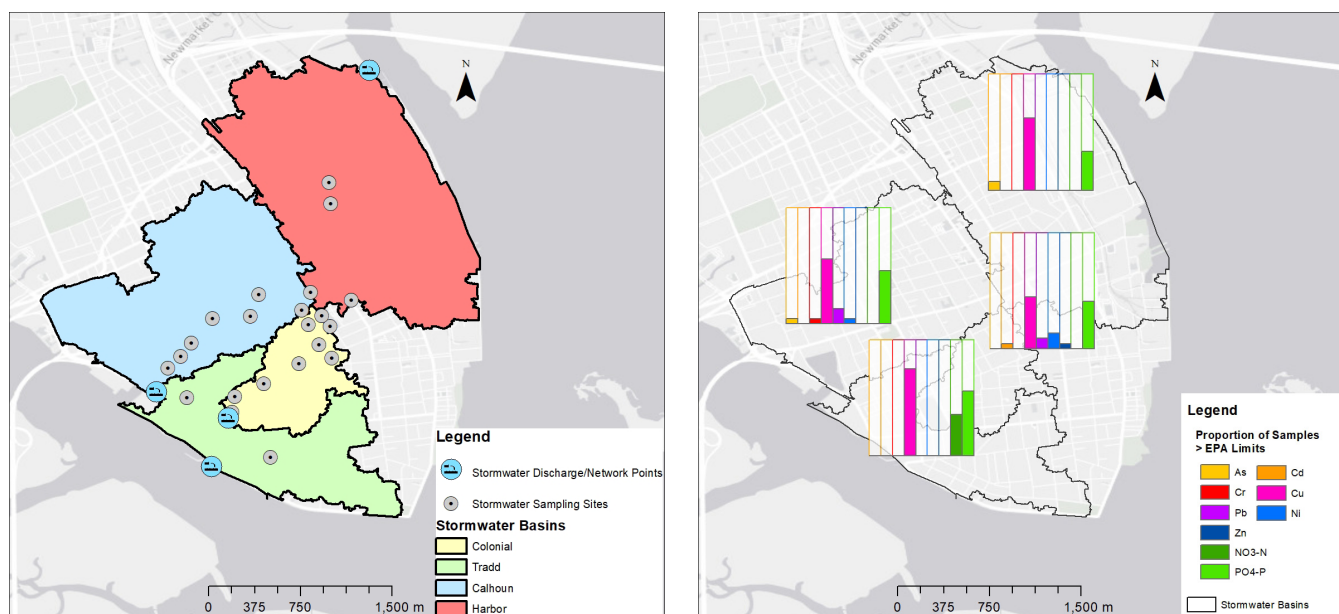


Figure 2. On the left, stormwater basins (four subwatersheds) delineated using lidar-derived digital elevation model (DEM) analysis. The city of Charleston's stormwater discharge outlets are also shown. On the right, the major trace metal and nutrient contaminants are highlighted in each of these watersheds. The bars indicate the percentage of samples that exceeded a US EPA standard or recommendation. Enterococci data are not shown here as all samples in all subwatersheds exceeded US EPA standards. Map data sources: USGS, SC DNR, and the city of Charleston.

Identification of Stormwater Pollution Hotspots in Charleston Peninsular

Table 1. The city of Charleston's interactive zoning map was used in conjunction with digitized basins from their master flood plan to describe the four areas sampled for this study.

Subwatershed	Area	Commercial	Residential	Industrial
	km ²	%	%	%
Colonial	0.6	24.7	75.3	0
Tradd	0.8	6.6	93.4	0
Calhoun	1.5	41.9	56.6	0.5
Harbor	1.4	32.6	32.4	35

Note. Residential land includes all land zoned as single-family, double-family, mixed-use residential, diverse residential, and residential offices.

Table 2. Enterococci statistics for the four subwatersheds.

Subwatershed	n	Minimum	Mean	Median	% RSD	% High
		MPN per 100 mL				
Colonial	21	2,500	17,850	24,196	44	52
Tradd	10	860	14,492	17,697	66	30
Calhoun	21	1,530	17,637	24,000	47	48
Harbor	11	8,010	22,432	24,196	22	82

Note. *n* is the number of samples collected, *Minimum* refers to the minimum MPN value determined over the entire sampling period, and *Mean* and *Median* refer to statistics conducted on the dataset over the entire sampling period. % High refers to the proportion of samples exceeding maximum high detection limit of 24,196 MPN per 100 mL. Every sample collected exceeded the SCDHEC's recreational standard for enterococci in marine waters of 104 CFU per 100 mL for a single sample.

named for the streets and landmarks in their area; the Calhoun subwatershed flows into the Charleston Marina, the Tradd subwatershed into the mouth of the Ashley, the Colonial subwatershed to Colonial Lake, and the Harbor subwatershed to the Cooper River. The land use in each basin was determined from the city of Charleston's zoning maps (<https://gis.charleston-sc.gov/interactive/zoning/>) and was categorized as residential, industrial, or commercial. Table 1 shows the percent of each subwatershed zoned for these uses. All sites were considered "urban" or "built-up," and the most common land uses within this urban environment are residential and commercial. Only the Harbor Basin had a significant proportion of industrial land, as a result of the Charleston Ports Authority cargo terminal along the Cooper River. The area of each subwatershed is listed in Table 1, and the subwatersheds averaged 1.1 km² in size. Significant pooling of stormwater runoff was observed at areas of low elevation in all subwatersheds.

STORMWATER QUALITY

The enterococci levels in every water sample collected were higher than any state or federal recreational water quality standard (Table 2). The average (arithmetic mean) of enterococci concentrations across all stormwater samples was 18,046 MPN per 100 mL. Even with 100-fold dilution, many water samples from many sites frequently exceeded the upper range on the Enterolert test method (i.e., every well in the Quantitray fluoresced under UV light). In the Harbor subwatershed, 82% of samples had at least 24,196 MPN per 100 mL. The average concentration in the Harbor subwatershed (22,432 MPN per 100 mL) was higher than the rest of the subwatersheds (Figure 3). The Tradd subwatershed has both the lowest average concentration (14,492 MPN per 100 mL) and the lowest percent of samples exceeding the detection limit (30%). However, there was large variability in enterococci concentrations, with some samples having as few as 860 MPN per 100 mL, and as such there was so much overlap between groups that no statistically significant differences between subwatersheds could be determined.

Every sample collected for this study had enterococci concentration higher than the SCDHEC recreational standard (S.C. Code Sections 48-1-10 et seq.) of 104 CFU per 100 mL (note that CFU and MPN values are equivalent). The average MPN counts were comparable to coastal stormwater studies in North Carolina, suggesting that high concentrations of fecal indicator bacteria are likely prevalent in the southeastern coastal plain (Parker et al. 2010).

We analyzed the “first flush” effect, where measured concentrations of an aqueous contaminant increase during initial stages of a storm following a dry period (Hathaway and Hunt 2011). This was not observed for enterococci concentrations in stormwater runoff; in fact, the opposite was true. A 2-sample T-test showed that the mean enterococci concentration of samples collected after 3-day dry periods was significantly lower than in those collected after more than 0.5 cm antecedent rainfall in the 3 days preceding (p-value = 0.013). Rain volume during the event itself (during the 24-hour period, which included sampling) did not appear to be related to the concentration of enterococci in stormwater runoff, unlike antecedent rainfall. Figure 3 highlights data collected with and without antecedent, and it appears that rainy days preceding sampling correlated positively with higher enterococci concentration. Average enterococci concentration was also observed to be higher in the late summer and fall. The average enterococci concentration for all our sites in September 2016 was 24,196 MPN per 100 mL and dropped to below 15,000 MPN per 100 mL from January 2017 until May 2017. By July 2017, the average enterococci concentration for all sites was comparable to the early fall 2016 high concentrations, before dropping again by January 2018. It was determined that the highest enterococci concentration in runoff was present after antecedent rainfall and during the summer and fall. Excessive enterococci concentrations were geographically distributed so that all subwatersheds exceeded US EPA regulations on enterococci concentrations for recreational water, although the Tradd Basin had lower concentrations of enterococci than other subwatersheds.

Trace metals were detected in all stormwater samples and at most sites. Of all trace metals that were analyzed, we consistently detected As, Cd, Cr, Ni, Pb, V, and Zn in most samples. Summary statistics for the detected concentrations of trace metals in stormwater sites are presented in Table 3. The relative standard deviation (RSD) of trace metal concentration within these samples was very high, indicating high variability. Table 3 also lists the maximum detected concentration of these trace metals and compares these concentrations to the US EPA’s chronic saltwater toxicity limits (US EPA 2020). Maximum detected trace metal concentration exceeded the toxicity limit of all trace metals, except V. For example, the average concentration of Cu among all samples was $24.0 \mu\text{g L}^{-1}$, which exceeds the US EPA’s chronic saltwater toxicity index of $3.1 \mu\text{g L}^{-1}$, and therefore, high Cu levels in

Charleston’s stormwater runoff would be a concern to aquatic life in the Charleston Harbor. Copper in the stormwater samples exceeded the chronic saltwater toxicity index for >45% of all samples collected in all subwatersheds. Five out of the remaining six trace metals exceeded the toxicity index in the Calhoun and Colonial subwatersheds. The Harbor and Tradd subwatersheds had either one or no trace metals (other than Cu) that exceeded the toxicity index. The spatial distribution of samples exceeding toxicity standards is plotted in Figure 2.

Previous studies positively correlate trace metal contamination in stormwater runoff to automobile traffic in the watershed (Aryal et al. 2010; Ma et al. 2016); hence, traffic data was also considered alongside trace metal data in stormwater. Annual daily traffic volume (AADT volume) data for the Charleston peninsula (SCDOT 2020) was used for the quantitative evaluation of the relationship between traffic and trace metal concentrations. Additional factors used were 3-day antecedent and event (24-hr) rain volume. Principal component analysis (PCA) was performed on the trace metal, precipitation, and traffic data to determine potential trends. In Figure 4, the first two principal components (PC1 and PC2), which accounted for less than half of the variance, and the correlation vectors for all variables studied are shown. Vectors within each quadrant are strongly correlated, indicating that traffic volume, 24-hr rain, and the trace metals As, Cd, Ni, and Pb are all positively correlated. Since vectors in adjacent quadrants are weakly correlated, there is a weaker but positive correlation between 24-hr rain and the other trace metals. Likewise, the data appears to support that 3-day antecedent rainfall is weakly, but positively, correlated with some trace metal concentrations (As, Cd, Pb, and Ni) and negatively correlated with the other trace metals (Cu, V, Zn, and Cr); that is, rain in the days preceding sampling is related to lower concentrations of these trace metals in runoff: a first flush effect. Also note that the trace elements that appear in each quadrant (e.g., As, Cd, Pb, and Ni) are likely to appear in water samples together and to a lesser degree with Zn, Cu, V, and/or Cr. Land use (industrial vs. residential vs. commercial) was not observed to significantly affect trace metal concentrations and was not included in the PCA biplot, but as illustrated in Figure 2, the Colonial and Calhoun basins were most likely to have samples exceeding toxicity standards for Pb and Ni. In these basins, 8 and 10 samples, respectively, were taken from sites with more than 5,000 average daily vehicles, while the Harbor and Tradd basins contained only one such sample each. The enterococcus data was also not included in the PCA analyses as every sample tested at every site had concentrations that significantly exceeded the SCDHEC’s recreational standard.

NO_3^- and PO_4^{3-} concentrations were used as nutrient chemical proxies in the stormwater samples and were averaged across each subwatershed. NO_3^- was present in >60% of the samples in all subwatersheds, while PO_4^{3-} was present in >35%

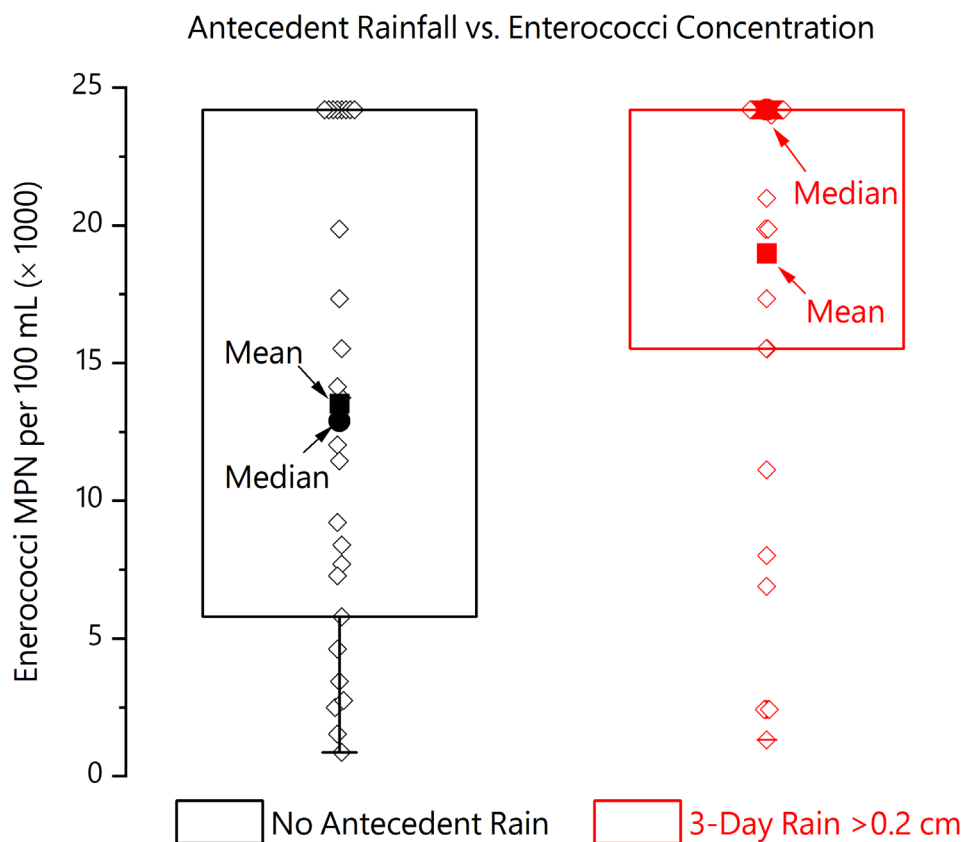


Figure 3. Box plot of enterococci concentrations in the stormwater runoff samples without (left) and with (right) antecedent rain (3 days prior to sampling). Mean (solid squares) and median (solid circles) values are also shown for each set of data. Overall, antecedent rainfall is positively correlated to the concentration of enterococci in stormwater runoff.

Table 3. Major trace metals of interest that were detected in the stormwater samples. Their concentrations varied significantly as shown in % RSD values. Not all trace metals were detected in every sample, as indicated below, and only concentrations that exceeded $0.1 \mu\text{g L}^{-1}$ were detected and reported. Detected concentrations were compared to the US EPA's chronic saltwater (SW) toxicity standards. Concentrations that exceeded the chronic saltwater toxicity are highlighted in red.

	As	Cd	Cr	Cu	Ni	Pb	V	Zn
Maximum, $\mu\text{g L}^{-1}$	71.6	16.3	82.1	146.2	26.2	41.5	14.0	142.4
Mean, $\mu\text{g L}^{-1}$	4.8	0.7	7.4	24.0	2.5	4.8	6.0	31.1
Median, $\mu\text{g L}^{-1}$	1.3	0.2	3.3	12.1	1.1	2.4	5.0	22.5
% RSD	254	357	174	124	180	156	70	92
% detection	75	60	76	69	79	84	43	84
SW Tox Std, $\mu\text{g L}^{-1}$	36	7.9	50	3.1	8.2	8.1	–	81

PCA Biplot

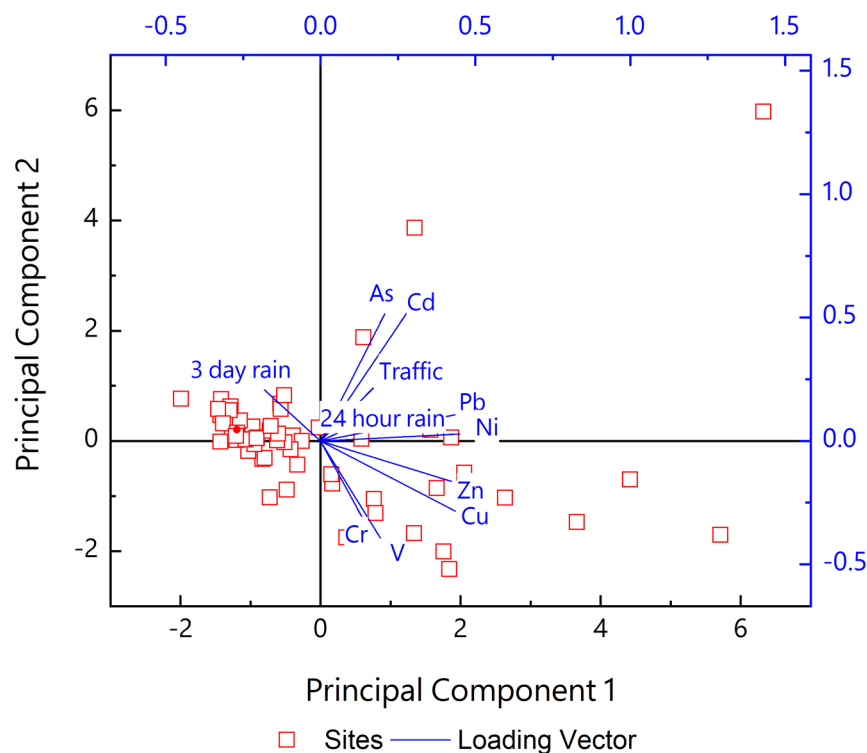


Figure 4. Principal components biplot showing sample clusters and loadings (vectors) between principal components 1 and 2. The data included for these analyses include trace metal concentrations, event rainfall, antecedent rainfall, and traffic counts. Vectors within each quadrant are strongly correlated, while vectors in the diametrically opposite vectors are inversely correlated. Vectors in adjacent quadrants are weakly correlated.

Table 4. Summary statistics of NO_3^- -N and PO_4^{3-} -P concentrations in stormwater samples from the four subwatersheds.

NO_3^- -N, mg L ⁻¹						
Subwatershed	n	Maximum	Mean	Median	% RSD	% Detection
Colonial	22	0.55	0.23	0.27	81	67
Tradd	9	3.5	0.94	0.35	148	78
Calhoun	23	0.50	0.28	0.32	53	83
Harbor	12	0.50	0.28	0.29	57	82
PO_4^{3-} -P, mg L ⁻¹						
Subwatershed	n	Maximum	Mean	Median	% RSD	% Detection
Colonial	22	1.21	0.25	0.00	165	38
Tradd	9	3.46	0.71	0.36	148	55
Calhoun	23	1.47	0.23	0.00	118	48
Harbor	12	0.50	0.15	0.00	139	36

Note. NO_3^- and PO_4^{3-} concentrations were converted to NO_3^- -N and PO_4^{3-} -P concentrations to allow comparisons to US EPA standards. All concentrations are in mg L⁻¹, *n* is the number of samples analyzed, % RSD is relative standard deviation in all samples measured within the subwatershed, and % Detection refers to the percentage of samples that contained detectable concentrations. Detected concentrations were compared to the US EPA's nutrient criteria. Concentrations that exceeded the nutrient criteria are highlighted in red.

of all the samples analyzed (Table 4). The concentrations ranged from 0.91-15.7 mg L⁻¹, while concentrations ranged from 0.94-10.6 mg L⁻¹. The Tradd subwatershed had the highest average concentration for both anions, but it also had higher variability (% RSD) between sample concentrations. The Tradd subwatershed is primarily zoned for residential use (Table 1) and has a higher density of historical homes with immaculately landscaped lawn and garden spaces compared with the other subwatersheds. A t-test did not show a significant change in mean NO₃⁻ and PO₄³⁻ concentrations after antecedent dry conditions versus 3-day rainfall >0.2 cm.

The US EPA's nutrient criteria recommendations for maximum total N and P in the Southeastern Coastal Plain are 0.9 mg L⁻¹ and 0.04 mg L⁻¹, respectively (US EPA 2000). The NO₃⁻ - N concentration in the Tradd subwatershed was higher than the US nutrient criteria recommendation; however, none of the other subwatersheds exceeded this recommendation on any samples. The mean PO₄³⁻ - P concentration in all subwatersheds was higher than the US EPA's nutrient criteria recommendation.

DISCUSSION

The goal of this study was to evaluate the usefulness of stormwater monitoring in identifying geographically high-risk areas for stormwater runoff pollution. As hypothesized, the urban footprint of the area resulted in significant pollution of the stormwater runoff.

The automatic GIS-based watershed delineation, which relies on high-quality elevation data (DEM), may have inherent artifacts or biases. At the time of this study, only a 2.5-m resolution lidar data was available, and the more recent 1-m resolution lidar data may likely provide additional insights during the watershed delineation (Gillin et al. 2015; Thomas et al. 2017). However, considering the rapid changes that have occurred to the built landscape of peninsular Charleston in recent years, the lidar data would have to be reassessed periodically for changes to the landscapes. Other inherent artifacts and inaccuracies are also reported in the use of various GIS-based watershed delineation methods such as the ArcHydro tool, the Hydrology toolset, and the ArcSWAT tool (Ray 2018). Other researchers may consider a systematic review of the different delineation methods for highly urbanized areas such as Charleston.

Fecal indicator bacteria or FIB (enterococci) levels were very high in stormwater runoff in all subwatersheds, regardless of the predominant zoning within the subwatershed. The most significant cause for impairment of all coastal waters in South Carolina and other similar locations is fecal bacteria (Chen and Chang 2014; Hathaway et al. 2010; SCDHEC 2018). Potential culprits for these high levels are pet waste, wildlife, and failing septic or sewage infrastructure (Steele et al. 2018), though septic infrastructure has been replaced

with municipal sewer systems in the Charleston peninsula. The presence of these bacteria poses a significant health risk to residents of these communities who may be exposed to the potentially harmful, pathogen-rich stormwater (Gaffield et al. 2003). Studies have pointed to not only the impairment of the final receiving water bodies (e.g., Charleston Harbor), but also the increased presence of antibiotic-resistant bacteria leading to serious health outcomes (Ahmed et al. 2018; Gaffield et al. 2003; Lee et al. 2020; Scott et al. 2016; Webster et al. 2004). Recent studies also suggest that the risk of human exposure to virulent pathogens such as *Vibrio* is increasing due to climate change-related impacts in coastal regions (Deeb et al. 2018).

Antecedent rainfall had a positive correlation to the presence of enterococci in stormwater and was also observed in other studies (Chen and Chang 2014; Hathaway et al. 2010; McCarthy et al. 2012; Siewicki et al. 2007). Higher average enterococci concentrations were also observed in late summer and fall, during which time this region generally experiences higher rainfall (Prat and Nelson 2014). Total suspended solids or TSS (not analyzed in this study) are positively correlated with FIB levels, and higher precipitation and strong flowrates generate higher TSS in runoff (McCarthy et al. 2012; Surbeck et al. 2006). Some studies have shown that the "first-flush" effect may not generate high concentrations of FIB in stormwater (Hathaway and Hunt 2011). It was suggested in these studies that antecedent climate conditions, including atmospheric moisture conditions, positively correlated with the survival rates of bacteria. Larger bacteria peaks are often associated with runoff associated with storms that have antecedent rainfall.

The trace metals observed in the stormwater runoff are some of the commonly observed nonpoint source pollutants in urban runoff, and the trends observed in this study align with reported data in other studies (Baalousha et al. 2019). In this study, the average trace metal concentrations did not appear to be excessive based on the US EPA's recommended ecological standards; however, these lower concentrations may be misleading. We analyzed trace metals in filtered water samples (< 0.22 μ) and not in the composited stormwater samples, which would account for trace metals associated with TSS and other particles such as organic matter. Trace metals strongly bond with a variety of environmental surfaces, including clay minerals, mineral oxides, and organic surfaces (Djukić et al. 2016; Hengren et al. 2005; Vulava et al. 2019). These trace metal-contaminated solids can remain suspended in the final receiving bodies, depending on the specific gravity of the suspended solid, and eventually settle out of the water column into the bed sediment. It is highly plausible that the overall chemical contaminant loads in the stormwater runoff is significantly higher than the concentrations reported in this study. In future studies, it would be useful to measure trace metal concentrations in bulk stormwater

samples. The presence of trace metal-contaminated estuarine sediment in the Charleston estuary is well documented and was reported to be higher near urban watersheds (Sanger et al. 1999). In addition, these trace metals may potentially enhance antibiotic resistance in bacteria, including enterococcus and *Vibrio* bacteria. Baker-Austin et al. (2006) found that the presence of trace metal contamination is a chronic and recalcitrant selection pressure with both environmental and clinical importance that may contribute to the maintenance and spread of antibiotic resistance in aquatic environments.

Nutrient pollution has long been identified as a significant degrader of coastal water systems across the US and the world, resulting in eutrophication, harmful algal blooms, shellfish poisoning, and fish kills (Howarth et al. 2000). Typical sources in urban watersheds include lawn fertilizer use and subsequent runoff of excess or improperly applied fertilizer (Toor et al. 2017). Recent studies demonstrate that nearly 80% of P and 20% of N from lawn fertilizer application are part of stormwater runoff in urban watersheds (Hobbie et al. 2017). Higher nutrient inputs were observed in the highly residential Tradd subwatershed; however, higher P concentrations were observed in all subwatersheds. Nutrient ions can also be associated with higher TSS in surface runoff due to the charged nature of the nutrient ions the environmental particles (Sparks 2003; Vaze and Chiew 2004; Wijesiri et al. 2019). Regionally, high concentrations of contaminants associated with stormwater runoff also deposit a wide range of contaminants into the ubiquitous stormwater retention ponds in the region (Beckingham et al. 2019; Cotti-Rausch et al. 2019).

Currently, the main strategy of managing stormwater in the general study area is to quickly pump the water into Charleston Harbor, which has reduced severe flooding in the area. However, flooding still occurs periodically following short and intense storms, especially during spring tides, and can overwhelm the area (Musser et al. 2016). Coastal regions also experience sunny day or “nuisance” flooding due to higher-than-normal spring tides (typically MLLW >7 ft) or King Tides (Román-Rivera and Ellis 2018) and increasingly higher seawater thermal expansion (Widlansky et al. 2020). In the last several years, such flooding has increased significantly in the Charleston peninsula and in other similar coastal areas (Morris and Renken 2020). Predicted and observed tidal data obtained from <https://mycoast.org/sc> show that King Tides are increasing in frequency near the Charleston peninsula, with more than 70 observations of MLLW >7 ft each year from 2016 to 2018. The resulting higher coastal water table elevations can potentially lead to increased backup of stormwater during coincident precipitation events.

The flooding-related problems also predominantly affect lower-income and minority communities in Charleston, as is the case in other urban areas of the US (Montgomery and

Chakraborty 2015). More effective best management practices (BMPs) and strategies need to be incorporated into sustainable and socially equitable stormwater management plans (Ahmed et al. 2019; Allen et al. 2019; Prudencio and Null 2018). The data collection and mapping framework used in this study can be used in the development of effective plans.

CONCLUSIONS

There is widespread contamination of stormwater runoff in urban areas such as the city of Charleston. Fecal bacteria are present at extreme levels and can pose a significant health risk to local communities. Trace metals and nutrient contamination are also present in the stormwater runoff at relatively high concentrations and can potentially enhance the antibiotic resistance of the fecal bacteria. Collectively, these contaminants, as well as other persistent and emerging contaminants that were not monitored in this study (e.g., persistent organic contaminants, microplastics), pose a significant threat to the coastal ecosystems. The resulting economic impact could be detrimental to important ecosystem services, such as recreation and seafood safety within the region. Stormwater runoff will add to the increasing coastal flooding, which is expected to only become worse due to the rapidly changing climate; therefore, innovative and sustainable solutions have to be investigated. Traditional strategies to reduce flooding and managing stormwater require significant infrastructure improvements and overcome significant technical challenges. However, protecting public health by reducing exposure to stormwater runoff and associated nonpoint source pollution is paramount.

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Identification of Stormwater Pollution Hotspots in Charleston Peninsular

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Identification of Stormwater Pollution Hotspots in Charleston Peninsular

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Enterococci Contamination on Edisto Island, South Carolina: Frequency, Sources of Contamination, and Prospects on How to Improve Water Quality

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Abstract. Beach monitoring samples were collected from 18 (14 currently in use) locations on Edisto Island, South Carolina, from 2000 to 2016 to assess patterns of water quality violations (contraventions) indicated by the presence of multiple *Enterococcus* species, including *Enterococcus faecalis* and *Enterococcus faecium*, bacteria used to assess the health of surface waters for contact recreation. Statistical analyses were conducted comparing Enterococci levels and different environmental variables including location, tidal stages, wind direction, and time. Specific focus was placed on temporal and spatial patterns for dates when the bacteria levels exceeded 104 Most Probable Numbers (MPN) per 100 milliliters (ml), which is the *Enterococcus* single sample maximum (SSM) water quality standard in South Carolina.

Results indicated that 2.2% of the samples exceeded the *Enterococcus* SSM standard and that the majority of these SSM contraventions occurred in September, during periods without significant rainfall but when primarily easterly winds occurred, at or near the time of flooding associated with King Tides (flood tides higher than 7.5 ft). Statistical analysis indicated that wind direction and tidal stage (at or around high tide— $\frac{3}{4}$ flood to $\frac{1}{4}$ ebb) appeared to have more of an impact on bacterial levels than rainfall, per se.

Microbial source tracking using quantitative polymerase chain reaction (qPCR) analysis was conducted and used to identify potential bacterial pollution sources causing Enterococci levels to exceed the SSM. Results indicated that birds and domestic dogs, rather than humans, were the major sources of bacterial pollution. These findings suggested that flooding during King Tides inundated a larger area of the beach-face surface containing bird and dog waste, which resulted in elevated levels of *Enterococcus* SSM contraventions, primarily on the southern end of the island. These findings are particularly relevant due to the increasing sea-level rise associated with climate change.

Changes in population growth on Edisto Island were also analyzed and indicated that permanent population has been increasing at a relatively low rate, while high rates of tourism growth have been observed and may play a factor in observed increases in Enterococcus SSM contraventions. Comparisons of contact recreational water quality with other South Carolina (SC) beaches indicated that Edisto Island (2.2% of *Enterococcus* SSM contraventions) was third only behind the Grand Strand (10.9%) and Sullivan's Island (3.9%), both of which have much higher population densities (777–1,300 people/sq. mile) compared to Edisto Island (36 people/sq. mile). These low population densities at Edisto Island and microbial source tracking results further indicate that most pollution sources were from birds and dogs and indicate the important role of coastal flooding associated with climate change. Coastal flooding is continuing to significantly increase as 24.4% of all King Tide flooding events in Charleston, South Carolina, over the past 67 years have occurred from 2019 to 2020. Better management of microbial pollution sources from dogs and birds is essential to prevent further degradation and loss of ecosystem services.

INTRODUCTION

Bacteria are often major causes of water quality impairments throughout the United States (Scott et al. 2002; Chenier et

al. 2009; EPA 2019). Increases in bacteria levels may cause gastrointestinal illness, as well as other diseases such as meningitis and upper respiratory infections. Many bacteria are also frequently resistant to antibiotics used to treat these

infections (Jernigan et al. 2020). Major sources of microbial contamination include humans, dogs, livestock, and wildlife (Webster et al. 2013; Araujo et al. 2014; Staley et al. 2014).

Indicator bacteria, common in the intestines of warm-blooded animals, are used as water quality measures to assess levels of water contamination (Colford et al. 2007; SCDHEC 2014, 2015, 2016). Results of indicator bacteria sampling are used to estimate risk of gastrointestinal illness associated with state-specified designated uses. Based on the results, bodies of water can be classified as fully supported, impaired, or threatened with respect to each of their designated uses (US EPA 2016).

Numerous species of disease-causing or pathogenic bacteria may contribute to water pollution in impaired or threatened waters and may emanate from different sources including humans, livestock, wildlife, and dogs. Multiple molecular genotypic assays, including real-time polymerase chain reaction, can be used to identify sources of bacteria pollution within a watershed that may aid in more effective management of pollution sources (Griffith et al. 2003; Stewart-Pullaro et al. 2006; Chern et al. 2009).

Edisto Island is a major tourist destination along the South Carolina coast and has recently seen contraventions that exceed the *Enterococcus* SSM contact recreation water quality standard (Table 1). An analysis of historical water quality monitoring data collected by the South Carolina Department of Health and Environmental Control (SCDHEC) for Edisto Island was conducted to identify better factors contributing to increased levels of bacterial pollution threatening water quality in this region. The objective of this study was to identify significant environmental variables that may cause these recent increased levels of pollution at Edisto Island.

METHODS

Water quality data collected for recreational contact monitoring (e.g., Enterococci) by the SCDHEC for Edisto Island in South Carolina were analyzed using data from 2000 to 2016 to determine spatial and temporal changes at each sampling station, including identification of locations with bacterial impairments.

The prescribed season for contact recreation water quality monitoring at Edisto Island runs from May to October each year, and all data collected during those months from 2000 to 2016 were analyzed (Chestnut 2018). The frequency of sampling at each location was dependent upon the degree of contact recreation and potential sources of pollution, with the most heavily used beaches and or those with the highest levels of pollution sources being monitored more frequently. Tier 1 beaches are sampled weekly, whereas Tier 2 beaches are sampled twice a week. Tier 2 beaches are sampled more frequently because they are considered more polluted. They

also differ in terms of land use; tourists use Tier 2 beaches more frequently.

A total of 18 stations (LC-075 through LC-082, 4 of which are no longer in use) were assessed, extending from the northeastern section of the coastline to the southwestern section of the coastline (Figure 1). At each site, water samples were collected and enumerated for *Enterococcus* levels using the Idexx Enterolert method prescribed by the EPA (2016, 2019) and the SCDHEC (Chestnut 2018), with results reported as Most Probable Numbers (MPN) per 100 milliliters (ml) of sample. The Idexx Enterolert method is a derivation of the EPA *Enterococcus* Method 1600 used to enumerate Enterococci. Other environmental measurements, such as rainfall (mm/day), tidal stage, and wind direction were also recorded (SCDHEC 2015).

The single sample maximum (SSM) of 104 MPN of Enterococci/100 ml was used to determine the frequency of contraventions. The number of *Enterococcus* SSM contraventions was determined for each station, as well as the overall arithmetic and geometric means (GM) of Enterococci concentrations for each site. In addition, samples with *Enterococcus* levels above 500 MPN/100 ml (above the Enterococci maximum) were also noted, along with maximum MPN/100 ml levels at these sites. These data were further subdivided into two temporal time strata to compare historical (2000–2010) versus more recent (2011–2016) changes, respectively. For each sampling date where the Enterococci MPN/100 ml exceeded the SSM or the maximum value of 500 MPN/100 ml, tidal stage and meteorological data (e.g., wind directions) were noted at the time of sampling. Historical tidal height data were not readily available for Edisto Island; thus, historical tidal heights for Edisto Island were estimated using data from the Cooper River entrance in Charleston, for which data were available, from the NOAA National Water Level Observation Network that were corrected using current NOAA tidal prediction results for Edisto Island (NOAA 2018).

POPULATION GROWTH

The relationship between population growth and tourism on Edisto Island pollution was also examined using data collected from the Edisto Chamber of Commerce. Data were analyzed in two different time periods: historical (2000–2010) and more recent (2011–2016); these were compared with similar temporal analysis of *Enterococcus* SSM contraventions. Comparison of changes in Enterococci levels at other South Carolina locations, including Charleston, Kiawah, the Grand Strand, and Hilton Head Island, were also included for spatial analysis throughout the coastal zone of SC.

MICROBIAL SOURCE TRACKING

Water samples (250 milliliters) were collected during 2016 and 2017 for microbial source tracking from locations where

Table 1. Basic Statistics of Beach Monitoring Stations

Site	Sample size	% of samples > 104 MPN per 100 ml	% of violation > 500 MPN per 100 ml	Average MPN of Enterococci (MPN/100 ml) (Mean \pm SE)	Geometric Mean of Enterococci (MPN/100 ml)* *Without Zero values	Maximum value for Enterococci at Each Site (MPN per 100 ml)	Date of Maximum Enterococci Value	Wind Direction on Date of Maximum Enterococci Value	Rainfall on Date (\pm 24h) of Maximum Enterococci Value (inches)
LC-075	132	0 a, b	0 a	16.1 (\pm 2.2) b, d	13.3 a, b	104	9/28 2004	NE	NA
LC-076	178	1.1 b, c	0 a	15.6 (\pm 3.13) b, f	12.4 b, c	173	8/4 2008	Calm	NA
LC-077	181	1.1 a, b	0 a	17.2 (\pm 4.55) b, f	12.9 a, b	148	9/28 2004	NE	0.0
LC-077A	132	1.5 a, b	0 a	14.9 (\pm 3.86) b, f	12.1 a, b	144	9/27 2011	SW	0.0
LC-077A1	29	0 a, b	0 a	12.4 (\pm 1.92) a, b	11.5 a, b	30 (twice)	7/2 2005; 7/25 2006	SW, SE	0.0
LC-077A2	118	0 a, b	0 a	13.4 (\pm 2.51) b, f	11.8 a, b	96	9/27 2011	SW	0.0
LC-077B	133	2.3 a, b	0.75 a	17.2 (\pm 10.2) a, b	11.9 a, b	521	5/5 2015	East	0.0
LC-077C	28	0 a, b	0 a	7.7 (\pm 3.3) a, b	18.1 a, b	86	6/11 2007	SW	0.0
LC-078	180	1.7 b, c	0 a	15.4 (\pm 3.07) b, f	12.1 b, c	171	9/29 2015	East	0.0
LC-078A	28	0 a, b	0 a	10.4 (\pm 1.54) a, b	10.3 a, b	20	5/16 2005	NE	0.0
LC-078B	118	1.7 a, b	0.85 a	23.6 (\pm 17.1) a, b	13.0 a, b	809	9/29 2015	East	0.03
LC-078C	28	3.6 a, b	0 a	14.7 (\pm 10.5) a, b	11.2 a, b	132	7/5 2006	Calm	0.0
LC-079	177	0.56 b, c	0 a	15.1 (\pm 3.05) b, f	12.2 b, c	213	9/28 2004	NE	0.0
LC-079A	89	0 a, b	0 a	16.8 (\pm 3.54) b, f	12.9 a, b	86	9/27 2011	SW	0.0
LC-080	181	2.2 a, b	1.1 a	24.4 (\pm 9.08) a, b	13.9 a, b	537	9/28 2004	NE	0.0
LC-080A	141	7.0 a, d	2.1a	65.9 (\pm 48.5) a, e	17.4 a, d	3255	8/9 2010	NE	0.0
LC-081	182	4.0 a, b	1.7a	31.7 (\pm 10.2) a, c	16.1 a, b	809	9/29 2015	East	0.03
LC-082	185	7.0 a, b	1.1a	53.8 (\pm 31.4) a, e	18.1 a, b	3873	7/9 2012	SW	0.0

Note. Mean, geometric mean, and maximum Enterococci bacterial concentrations (MPN/100ml) at each site on Edisto Island, 2000–2016, along with date, wind directions, and rainfall data when maximums occurred. Sites bolded had the highest levels of Enterococci. Statistical differences between sites, based on both analysis of variance and pairwise t-tests, are indicated by different letters (a, b, c, d). The letter a indicates no difference, b is different from a, c is different from a and b, and d is different from a, b, and c. SE=standard error. MPN=most probable number. NE=northeast. SW=southwest. SE=southeast.

Enterococci Contamination on Edisto Island, South Carolina

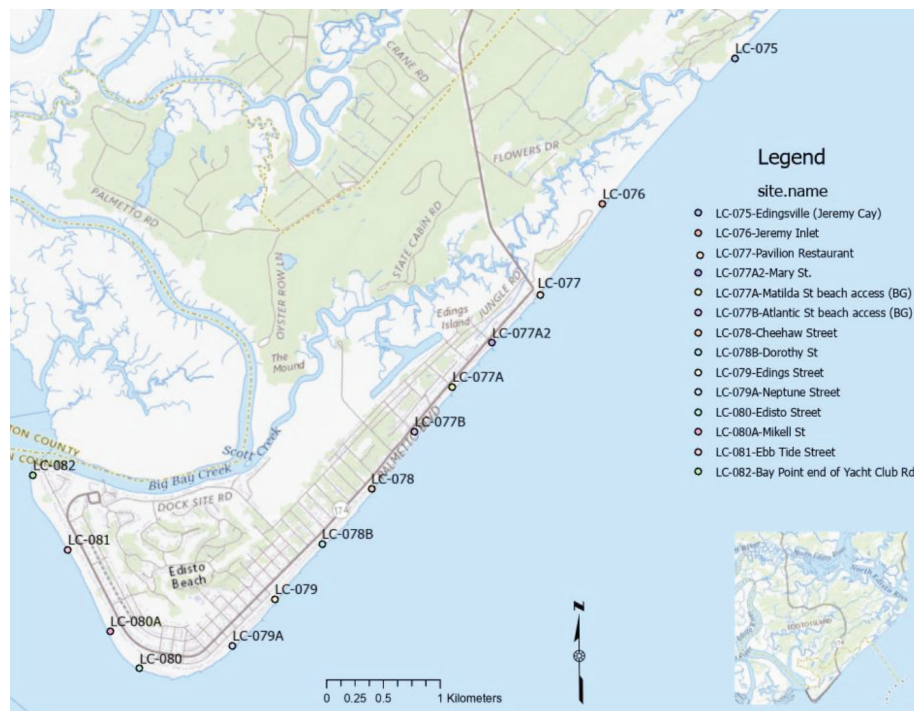


Figure 1. Current SCDHEC beach monitoring stations on Edisto Island, South Carolina. The map displays the 14 **current** beach monitoring stations. Four of the stations (LC-077A1, LC-077C, LC-078A, and LC-078C) are no longer in use. LC-077A1 and LC-077C are between LC-077 and LC-078. LC-078A and LC-078C are between LC-078 and LC-079. Note the location of Big Bay Creek, where many of the stations with higher numbers of Enterococci and frequencies of contraventions occurred near station LC-082. Map courtesy of Ronald Willis.

the *Enterococcus* SSM contravention results indicated the most frequent and highest violation of SSM standards (LC-081 and LC-082). The qPCR tests indicated the origin of the Enterococci bacteria in the samples. All water samples were placed on ice and transported to the laboratory for processing within 6 hours of collection. The samples were sent to the Source Molecular Lab in Florida for analysis. Data were only available for Edisto stations from 2016 and 2017, and qPCR results were therefore limited. The qPCR source tracking method can distinguish between humans, domesticated animals (e.g., dogs, cows, pigs, horses, and chickens), and wildlife (e.g., beavers, geese, gulls, and ruminants—deer, elk, goats, and sheep) microbial pollution sources. Although Source Molecular's techniques are proprietary, a general description of the qPCR method is as follows. Water samples were filtered (using 0.45- μm -pore-size, 47-mm-diameter filters) for DNA extraction and filters were frozen at -80°C until they were ready for DNA extraction. Filters were then placed into tubes, and the filter contents were extracted using DNA isolation kits according to the manufacturer's instructions. Blanks were included in each batch of DNA extractions. qPCR assays were performed on all extracted DNA samples (including filtration and extraction blanks). Reactions were carried out in 96 well plates, which included

samples, negative controls (nuclease-free water), and positive controls (e.g., DNA extracted from a known fecal source). For all plates, the negative control produced no band on the subsequent gel, while the positive control produced a band of the correct molecular weight for the corresponding target. Conditions were consistent with previously published assays (Bernhard and Field 2000; Green et al. 2004; Lu et al. 2008). Standard curves for each human, animal, and wildlife source were generated from known cultures and compared to sample results. All qPCR runs had an efficiency level between 90% and 110%, with an R^2 of > 0.95 , and results were normalized to reaction efficiency (Hagedorn et al. 2011).

STATISTICAL ANALYSIS

Statistical analysis included descriptive statistics (mean \pm standard deviations/standard errors for numeric variables and proportions for categorical variables) for *Enterococcus* and select environmental variables (e.g., wind direction, tidal stage) that were analyzed. For comparison of water quality differences among stations, analysis of variance (ANOVA) and pairwise t-tests with Bonferroni adjustment were conducted to detect significant ($p < 0.05$) differences between stations. Letters (a, b, c, d) were used to indicate differences in all figures and tables (see caption for Table 1).

To compare significant ($p < 0.05$) differences of proportions between the two time periods, two-sided chi-squared tests were used. Similarly, for comparisons of significant ($p < 0.05$) differences between proportions across tidal stages, two-sided chi-squared tests were also used. Although trend analysis could have been conducted, the strength of that method would have been enhanced by larger sample sizes for each station as well as longer time periods, which is why this method was not used. Earlier studies of trend analysis of > 30 years of shellfish harvesting monitoring data, using intervention analysis, showed that there must first be a determination of the exact type of change in trend before the appropriate trend model can be applied for analysis (Nelson et al. 2006). Tests on tides and winds were conducted both for the overall time period from 2000 to 2016 and for the dates when *Enterococcus* contraventions occurred. Due to limited data, only correlation coefficients could be obtained for some parameters, including rainfall. The correlation coefficient between tourism numbers and the number of contraventions for some years (2004, 2012, and 2016) was also determined. In addition, the correlation coefficient between coastal community population density and the number of contraventions was determined. The correlation coefficients between population density, maximum *Enterococci* value, and percentage of values above 500 MPN/100 ml were also calculated. All statistical analyses were performed using R 3.3.2 statistical software, and statistical differences with p -values < 0.05 were considered significant.

RESULTS AND INTERPRETATIONS

ANALYSIS OF BACTERIAL WATER QUALITY RESULTS

Between the years 2000 and 2016, 2,240 samples were collected and analyzed for *Enterococci* levels (see Table 1; note sample sizes for each station). Of these, 1,922 were analyzed; the other 318 samples were collected during time periods when state monitoring for contact recreation is not routinely conducted each year (November to April). Wide variations in *Enterococci* levels were observed across sites, with greater medians and geometric means of *Enterococci* observed at stations in the southern and western portions of the area. Like several sites in Myrtle Beach, Edisto Island has many outfalls and swashes that increase the risk for pollution. *Enterococci* levels at all station were highly variable with frequently extreme maximum values (>500 MPN/100 ml), indicating that data were highly skewed for some stations.

A total of 50 samples, or 2.6% of all samples, exceeded the *Enterococcus* SSM (above 104 MPN/100ml). The average MPN of these samples exceeding the SSM *Enterococci* standard was 436 MPN/100 ml (± 18.5 MPN/100 ml standard error), and they had a geometric mean of 254 MPN/100 ml. These results indicate that beach monitoring stations in the southern and western part of Edisto Island (stations 080A,

081 and 082) were significantly ($p < 0.05$) higher and more contaminated locations than those in the more northern and eastern stations; *Enterococci* levels at stations LC-075, LC-077A1, LC-077A2, LC-078A, and LC-079 never exceeded the SSM (Table 1). For example, for both the percentage (%) of stations under ($>$) the SSM (>104 MPN/100ml) and the geometric mean for *Enterococcus*, the only significant ($p < 0.05$) differences that were observed between stations was LC-080A on the western end of the island versus stations LC-076 and LC-078 on the more eastern portion of the island. Similarly, for the average *Enterococcus* MPN, stations LC-80A, LC-81, and LC-82 on the western end of the island were significantly ($p < 0.05$) different from stations LC-75, LC-76, LC-77, LC-77A, LC-77A2, LC-78, and LC-79 on the more eastern end of the island.

These three stations on the southern and western ends of the island—LC-080A, LC-081, and LC-082—each exceeded the *Enterococcus* SSM more times than all the other stations combined. Big Bay Creek flows near many of these impaired stations, suggesting that pollution sources within this body of water may be major sources of contamination. For example, station LC-082 is near the mouth of Big Bay Creek (Figure 1), as are sites LC-080A and LC-082, which are in adjoining areas. The highest average *Enterococci* level occurred at site LC-080A. These patterns suggest that tidal flushing occurred inland, as these areas tend to have marshlike characteristics.

Examination of temporal trends indicated that stations did not start exceeding the *Enterococci* SSM criteria until 2001 and beyond. No SSM *Enterococci* contraventions occurred in 2000, 2005, or 2016 (18.8% of the total samples). Temporal trends also indicated that most instances of *Enterococcus* SSM contraventions occurred between July and September of each respective year, although some occasionally occurred in May (Table 2; Figures 2 and 3). The general annual pattern observed was for *Enterococcus* levels to remain relatively constant with low *Enterococcus* SSM contravention levels (6–12%) from May to August and to then rise sharply in September (58%) with a subsequent decline in October (Figures 2 and 3). Most contraventions occurred during September as 58% (29 out of 50) of the samples for that month exceeded the SSM *Enterococci* standard that month throughout each year from 2000 to 2016. The frequency of the impairments continued to rise at some locations in September as temporal comparison of results for 2010–2016 versus 2000–2010 indicated (45.4% vs. 70.4% SSM contraventions, respectively; Table 2).

A total of 313 samples were collected in September from 2002 to 2016, and 9.3% exceeded the SSM for *Enterococci* (Tables 2; Figures 2 and 3), more than any other month. These findings indicate that nearly 1 out of every 10 samples collected during September exceeded the SSM. September is the peak of hurricane season when increased coastal flooding associated with the higher storm tides associated with the

Enterococci Contamination on Edisto Island, South Carolina

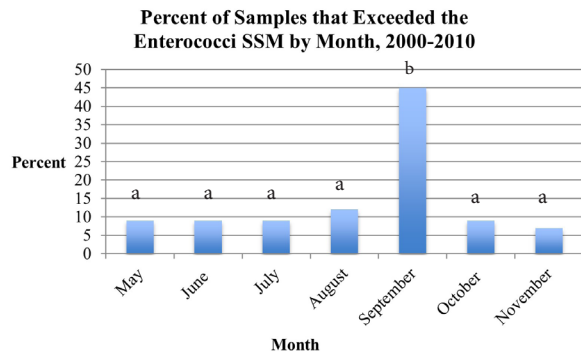


Figure 2. Percentage of SSM contraventions by month, 2000 to 2010. A total of 33 contraventions occurred from 2000 to 2010. Note that most contraventions of SSM Enterococci standards occurred during September (45.4%) for this time period. The percentage for September was significantly different from all other percentages, as indicated by different letters (a, b). Although November is outside of the usual sampling period for water quality monitoring, in that year a sampling event occurred early in the month (just beyond the end of the normal sampling period each year) and was included in these analyses.

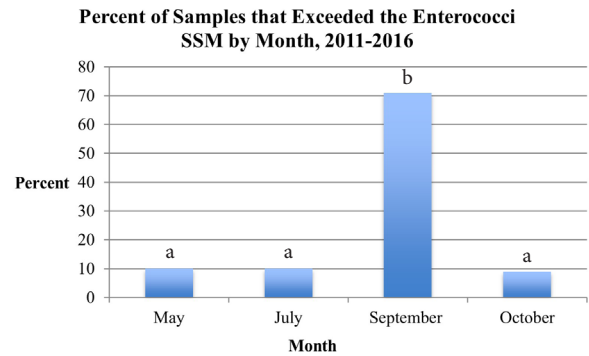


Figure 3. Percentage of samples for each month that exceeded the SSM for Enterococci from 2011 to 2016. A total of 17 contraventions occurred from 2011 to 2016. Note that the majority of SSM contraventions occurred in September (70.4%) during this time period. The percentage for September was significantly different from all other percentages, as indicated by different letters (a, b). There were no SSM contraventions in June and August during this time period.

Table 2. Total number of samples and percent of samples collected each month that exceeded Enterococci SSM standards, 2000–

Month	Total Number of Samples Collected	Total Number of Samples in the Month that Exceeded Standards	% of Total Number of Samples	Mean % Contraventions 2000–2010	Mean % Contraventions/Year 2011–2016
May	310	5	1.6 a	9 a	12 a
June	373	2	0.5 a	9 a	0 a
July	411	3	0.7 a	9 a	12 a
August	359	5	1.3 a	15 a	0 a
September	313	29	9.3 b	45.4 b	70.4 b
October	156	6	3.8 a	9 a	6 a
TOTAL	N=1,922*	N=50	2.6%	N=33 (66%)	N=17 (34%)

Note. Total number of samples and percent of samples collected each month that exceeded Enterococci SSM standards, 2000– 2016. Note that September was the month when the most frequent SSM Enterococci contraventions occurred (45–70%). The asterisk (*) indicates that the total number of samples excludes sampling during other times of the year. Temporal comparisons for historical (2000–2010) and more recent sampling (2011–2016) are also included. Months with different letters (a, b, c, d) were significantly ($p < 0.05$) different in statistical comparisons as described in Table 1.

Table 3. Meteorological Characteristics on Dates with Extremely High Enterococci MPNs

Station	Date	MPN	Wind Direction	Tide Stage
LC-077B	05/05/2015	521	East	¼ ebb
LC-078B	09/29/2015	809	East	¼ ebb
LC-080	08/09/2010	521	Northeast	½ ebb
LC-080	09/28/2004	537	Northeast	¾ flood
LC-080A	08/09/2010	3,255	Northeast	½ ebb
LC-080A	09/27/2010	644	South	¾ flood
LC-080A	09/30/2004	2,063	Northwest	¾ flood
LC-081	08/09/2010	691	Northeast	½ ebb
LC-081	09/27/2011	512	Southwest	¼ ebb
LC-081	09/29/2015	809	East	¼ ebb
LC-082	09/27/2011	752	Southwest	¼ ebb
LC-082	07/09/2012	3,873	Southwest	½ flood

Note. Location, date, Enterococci MPN level (MPN/100 ml), wind direction, and tide stage for the 12 samples that exceeded 500 MPN/100 ml levels of Enterococci. Notice the patterns in wind direction and tide stage. These maximum Enterococcus levels occurred primarily (66.7% of the time) around the time of flood tide (e.g., ¾ flood or ¼ ebb). The bold value indicates the maximum Enterococci level measured.

passage of hurricanes and tropical storms may occur (NOAA 2018), as well as a time when the maximum thermal expansion of seawater is observed along the southeastern US coast (IPCC 2014). September is also past the peak of the tourist season (June through August). Additional temporal analysis comparing historic (2000–2010) to more recent (2011–2015) time periods indicated that this trend of increased contraventions of the *Enterococcus* SSM was consistent over time (Table 2). Pairwise statistical comparisons indicated that the percentage of samples for September was significantly different from that of all other months, for both 2000–2010 and 2011–2016 (Table 2; Figures 2 and 3).

Immediate advisories are issued for areas when the Enterococci levels exceed 500 MPN/100 ml, above the

Enterococci maximum, and these Enterococci levels are generally indicative of more extreme levels of microbial pollution sources. From 2000 to 2016, 12 samples exceeded the *Enterococcus* maximum threshold of 500 MPN/100 ml, representing 24% of all dates for which there were Enterococci water quality contraventions (Table 3). Temporal analysis of these extreme values indicated that only two samples (17%) exceeded the *Enterococcus* maximum threshold of 500 MPN/100 ml for 2000 to 2010, while 10 (83%) of these Enterococci maximum contraventions occurred from 2011 to 2016.

Stations LC-080A and LC-081 had the greatest number of samples that exceeded 500 MPN/100 ml. The highest MPN value for Enterococci was 3,873 MPN/100ml, which occurred at LC-082, the station that is farthest to the southwest on Edisto Island. Most of these *Enterococcus* contraventions occurred around the time of flood tide, with 67% occurring from ¾ flood (just before flood tide) to ¼ ebb (just after flood tide). Similarly, the major (67%) wind direction was onshore easterly or northeasterly winds for most *Enterococcus* maximum contraventions. The findings suggest that the highest Enterococci concentrations occurred mostly during peak tidal stages. Onshore winds may result in higher tides that can flood lands containing large amounts of potential microbial pollution.

EFFECTS OF WIND DIRECTION ON ENTEROCOCCUS SSM CONTRAVENTIONS

Wind directions can impact bacteria levels through the scouring of sediments that may have microbes attached or adhering to the sediments (Hartel et al. 2005, 2007; McDonald et al. 2006). In most cases, the wind direction was either from the east (E), northeast (NE), or southwest (SW) on days when samples exceeded the Enterococci SSM maximum criterion (Table 1 and Figure 4). The wind direction on Edisto Island on dates when the SSM maximum criterion was exceeded shifted based on the years analyzed. Analysis of Enterococci SSM maximum contraventions from 2000 to 2010 indicated that the wind direction was primarily from the NE. However, for Enterococci SSM maximum contraventions from 2011 to 2016, the predominant direction was from the SW and E. The SW and NE wind directions are parallel to the shoreline as these contrasting predominant (NE winds with the highest velocity and generally of short duration associated with low pressure systems) and prevailing (SW winds that are of lower velocity for more sustained durations associated with high pressure systems) winds affect the orientation of barrier islands throughout South Carolina. This suggests that more flooding occurred during the 2011–2016 period leading to *Enterococcus* SSM contraventions during prevailing wind conditions, whereas, in the 2000–2010 time period, flooding resulting in *Enterococcus* SSM contraventions were generally associated with predominant wind conditions generally

Enterococci Contamination on Edisto Island, South Carolina

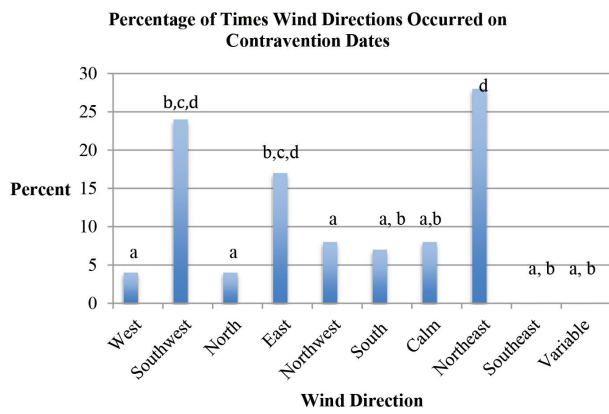


Figure 4. Wind direction on days with contraventions from 2000 to 2016. Stations with different letters (a, b, c, d) were significantly ($p < 0.05$) different. Statistical analysis indicated that these differences in percentages for NE, E, and SW winds were statistically significantly ($p < 0.05$) different from other wind directions on days when contraventions occurred. Most SSM Enterococci contraventions occurred when wind directions were generally onshore easterly and northeasterly winds associated with low pressure systems and resulting King Tides and tidal flooding or from prevailing winds from the southwest, generally associated with fair weather and high pressure systems.

associated with more intense weather systems. Easterly winds are onshore winds, which may enhance tidal heights and increase flooding at the time of high tide. These three wind directions (NE, E, and SW) occurred with more frequency than other wind directions in the overall data and more frequently on days where the Enterococci SSM maximum criterion was exceeded; they were significantly ($p < 0.05$) different from the other wind directions.

TIDE STAGE EFFECTS ON ENTEROCOCCUS SSM CONTRAVENTIONS

Chi-square analysis of tidal heights on the dates of SSM contraventions indicated that there were significant ($p < 0.05$) differences in the proportion of contraventions across different tidal stages, with the most common tidal stage appearing when *Enterococcus* SSM contraventions occurred around the time of high tide (e.g., $\frac{3}{4}$ flood to $\frac{1}{4}$ ebb). More than 50% of all contraventions occurred then (Figure 5 and Table 4). The $\frac{1}{4}$ ebb tides occur just after flood tide, which may flood land and erode sediment that contains bacteria from a variety of sources including humans, wildlife, livestock, and pets. Onshore winds often result in higher flood tide elevations that may inundate larger terrestrial areas, leading to larger quantities of pollutants potentially being discharged into tidal waters.

Tidal heights were higher than 6.5 feet (1.98 meters) on 90% of dates where Enterococci SSMs exceeded the standard (Table 4) and higher than 7 feet on 57.9% of these dates. King Tides, which are higher than 7.5 feet (Pietrafresca et

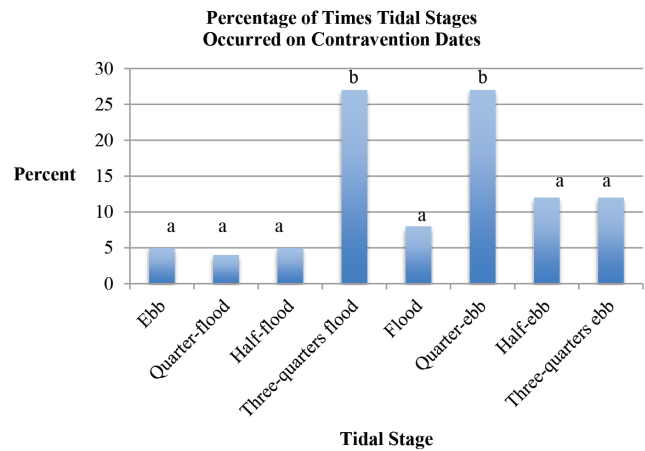


Figure 5. The percentage of times different tidal stages were sampled for the 50 samples where SSM contraventions occurred. The tidal stages are presented in increasing order, beginning with ebb and ending with flood, and then decreasing from flood back to ebb. Note the prevalence of $\frac{3}{4}$ flood and $\frac{1}{4}$ ebb during most contraventions and how SSM violation patterns change throughout the tidal stage. Statistical analysis indicated that the percentage occurrence of $\frac{3}{4}$ flood and $\frac{1}{4}$ ebb tides were significantly ($p < 0.05$) different from the percentage occurrence at other tidal stages when SSM contraventions occurred, as denoted by different letters (a, b).

al. 2015), occurred on 31% of these dates. Most of the high tides occurred in the late evening or early morning, when SSM *Enterococcus* contraventions also occurred (Table 4 and Figure 5).

RAINFALL EFFECTS ON SSM CONTRAVENTIONS

Interestingly, rainfall appeared to have a weak association with *Enterococcus* contraventions on Edisto Island. Rainfall events (within a 24-hour period of the Enterococci SSM contravention date) were only recorded on 11 (22%) of the 50 dates when samples exceeded the SSM criterion, primarily in September 2010 and 2015 (72%). The amount of rainfall for dates (+/- 24 hours to account for runoff periods) when SSM violation occurred ranged from 0 to 2.67 inches averaging 0.384 inches, much greater than the overall average amount of 0.056 inches for all sampling events (National Climatic Data Center 2015).

The Pearson correlation coefficient (r) between MPN and rainfall was only -0.268 . Such a weak coefficient indicated an inverse relationship between the variable as bacteria levels decreased with increasing amounts of rainfall. Rainfall can lead to increased bacterial counts due to stormwater runoff that results when rainfall rates and amounts are sufficient to cause significant runoff, generally > 0.50 inches (Pitt, 1999). Rainfall amounts > 0.50 inches only occurred on 6% of the dates when Enterococci SSM contraventions occurred (Table 1) and < 0.03 inches on the dates (+/- 24 hours) when

Table 4. Tidal Heights on Contravention Dates

Date of Violation	Time	Flood Tide Height Charleston, SC a (feet)	Flood Tide Height Edisto Island, SC b (feet)
5/9/2001	0200	6.855	7.38
10/15/2001	2354	7.052	7.577
9/3/2002	2130, 2136 (twice)	6.763	7.288
10/7/2002	1324	7.095	7.62
11/4/2002	1212	6.747	7.272
5/20/2003	0348	6.967	7.492*
9/28/2004	0024	7.216	7.741
9/30/2004	1400	6.176	6.701
6/11/2007	2130, 2136 (twice)	7.134	7.659
6/26/2007	2154, 2200, 2206 (three times)	5.628	6.153
7/16/2007	1412	4.939	5.464
10/08/2007	2318	6.12	6.645
6/3/2008	2354	6.73	7.235
8/4/2008	0236	6.429	6.954
5/19/2009	2100	6.261	6.786
7/12/2010	0030	6.96	7.485
8/9/2010	2354	7.416	7.941
9/27/2010	1536	6.222	6.747
9/28/2010	1525	6.137	6.662
5/16/2011	2348	6.803	7.328
9/27/2011	0054	6.714	7.239
7/9/2012	0448	5.477	6.002
10/1/2012	1330	6.133	6.658
9/17/2013	2306, 2318 (twice)	7.114	7.639
5/5/2015	0118	6.153	6.678
9/29/2015	1342	8.046	8.571

Note. Heights of flood tides at stations on dates when SSM *Enterococcus* contraventions occurred. Bold values indicate dates of King Tides when tidal elevations that exceed 7.5 feet in height and 31% of dates when SSM contraventions occurred. Occassions when the tidal heights occurred more than once are also noticed. a = Tidal Height for Charleston Harbor by NOAA. b = Tidal Height for Edisto Island which added a 0.525 foot correction to data from Charleston Harbor. *= Rounded up to 7.50 feet.

Enterococci Contamination on Edisto Island, South Carolina

maximum *Enterococcus* levels were measured at each station (Table 1).

MICROBIAL SOURCE TRACKING RESULTS

Microbial source tracking results using qPCR assays conducted in Big Bay Creek on Edisto Island, which had the maximum *Enterococcus* levels and contraventions, indicated that the primary sources of Enterococci bacteria were birds and domestic dogs (Table 5). Although the data did not indicate what types of birds were tested, it is likely that gulls were the main source of avian bacteria on Edisto Island, given the lack of farmland for chickens and geese. Only stations LC-081 and LC-082 were included in the microbial source tracking analysis because of the relatively higher levels of *Enterococcus* measured there (means ranged from 31.7 to 53.8 MPNs/100 ml, and geometric mean ranged from 16.1 to 18.1 MPNs/100 ml) and large proportion of samples exceeding the SSM. These sites are also the only areas directly influenced by Big Bay Creek as all other sites faced the ocean and had much lower mean (12.4 to 24.4 MPNs/100 ml) and geometric mean (10.3 to 13.0 MPNs/100 ml) *Enterococcus* and SSM levels that exceeded the standard. The dominance of dog and wildlife sources underscores the importance of physical factors identified in this analysis (e.g., wind direction, tidal stage, and rainfall) on the occurrence of water quality contraventions for Enterococci bacteria. Rainfall was rare during most Enterococci SSM contraventions and tidal flooding dates. These patterns suggest that extreme flood

tides, which inundate the land where wildlife and dog waste may reside, may play a significant role in water quality on Edisto Island.

LAND USE AND POPULATION GROWTH

Compared to other coastal areas of South Carolina, recent population growth on Edisto Island has been relatively slow. The population on Edisto Island increased from 2,288 in 2000 to 2,430 in 2016, a modest 6.2% increase (Table 6). The population density of Edisto Island is only 36 people per square mile. In contrast, the population densities of Charleston and Mount Pleasant are approximately 1,150 and 1,500 people/square mile, respectively (31 and 41 times more dense; United States Census Bureau 2017). Other SC coastal municipalities areas are also much more densely populated, including Kiawah Island (148 people/sq. mile), Folly Beach (209 people/sq. mile), Hilton Head Island (900 people/sq. mile), Sullivan's Island (717 people/sq. mile), and Myrtle Beach (1,300 people/sq. mile). The correlation coefficient between population density and number of contraventions was 0.719, indicating a strong positive correlation. The correlation coefficient between population density and maximum Enterococci values was 0.63, and the coefficient between population density and percentage of samples above 500 MPN/100 ml was 0.6; both are moderately strong positive correlations.

From 2004 to 2016, the total number of annual tourists at Edisto Island increased at a rate of greater than 14,000 visitors per year, increasing from 339,652 visitors per year to 505,748 visitors per year, a 48.9% increase (Table 6). The correlation coefficient between tourism visits and the number of contraventions for 2004, 2012, and 2016 was weak and negative ($r = -0.28$).

Enterococcus SSM contraventions at Edisto Island were 2.2%, but they were much higher in Myrtle Beach (10.9%) and Sullivan's Island (3.9%) and lower at Hilton Head Island (1.5%) and Kiawah Island (0.3%) (Figure 6). Conversely, Edisto Island had the second-highest maximum *Enterococcus* MPN of 3,873 per 100 ml among these South Carolina beach communities. Only Myrtle Beach had higher maximum *Enterococcus* levels of greater than 24,196 MPNs/100 ml (Table 7); the highest MPN the Enterolert test can register is 24,196 per 100 ml. That extreme value occurred at station WAC-001 in North Myrtle Beach in October 2017. Similarly, Edisto Island had the second-highest percentage of *Enterococcus* samples that exceeded 500 MPNs/100 ml (1.02%) among these South Carolina beach communities, as only Myrtle Beach had a higher percentage greater than 500 MPNs/100 ml (3.2%) (Table 7).

Table 5. Microbial Source Tracking Results for Edisto Island, 2016–2017

Site	Dates Sampled	Sources of Pollution
LC-081	10/25/16	Birds and dogs
LC-082	10/25/16	Birds
LC-081	11/29/16	Dogs
LC-082	11/29/16	Birds
LC-081	12/15/16	Birds
LC-082	12/15/16	Birds and dogs
LC-081	05/23/17	Birds
LC-082	05/23/17	Dogs
LC-081	06/14/17	Birds
LC-082	06/14/17	No sources detected
LC-081	06/27/17	Birds and dogs
LC-082	06/27/17	Birds and dogs

Note. Primary sources of microbial pollution at Edisto Island at sites with the most Enterococci SSM contraventions in 2016 and 2017. All sources were either dogs, birds, or both, and no human sources of bacterial pollution were observed.

Table 6. Resident and Tourist Populations on Edisto Island

Year	Population	Annual Tourist Visits
2004	2,288	339,652*
2012	2,408 (5.2% increase from 2004a)	441,164** (28.8% increasea)
2016	2,430 (6.5% increase from 2004b)	505,748 (48.9% increaseb)

Note. There were significant increases, especially in tourism. a = Increased population comparisons between 2000 and 2010; b = Increased population comparisons between 2000 and 2016; * = 2004; ** = 2012 Data from 2004 and 2012 are shown as surrogates for 2000 and 2008 data. Data from Edisto Island Chamber of Commerce.

Table 7. Comparison of Edisto Island with Other SC Coastal Sites with Respect to Water Quality Measures

Locations	Number of Contraventions	Number of Samples	Percentage of SSM Contraventions	Maximum Enterococci	Percent of samples > 500 MPN/100ml
Myrtle Beach	3055	28,027	10.9	>24,196	3.2
Kiawah Island	2	633	0.3	1918	0.15
Hilton Head Island	33	2186	1.5	959	0.2
Sullivan's Island	19	484	3.9	24	0.8
Edisto Island	50	1922	2.6	3873	1.05

Note. Edisto Island had the second-highest maximum Enterococci level reported statewide despite having the lowest population densities among these locations.

Percentage of SSM Contraventions by Month at Other Coastal Sites Compared to Edisto, 2000 through 2016

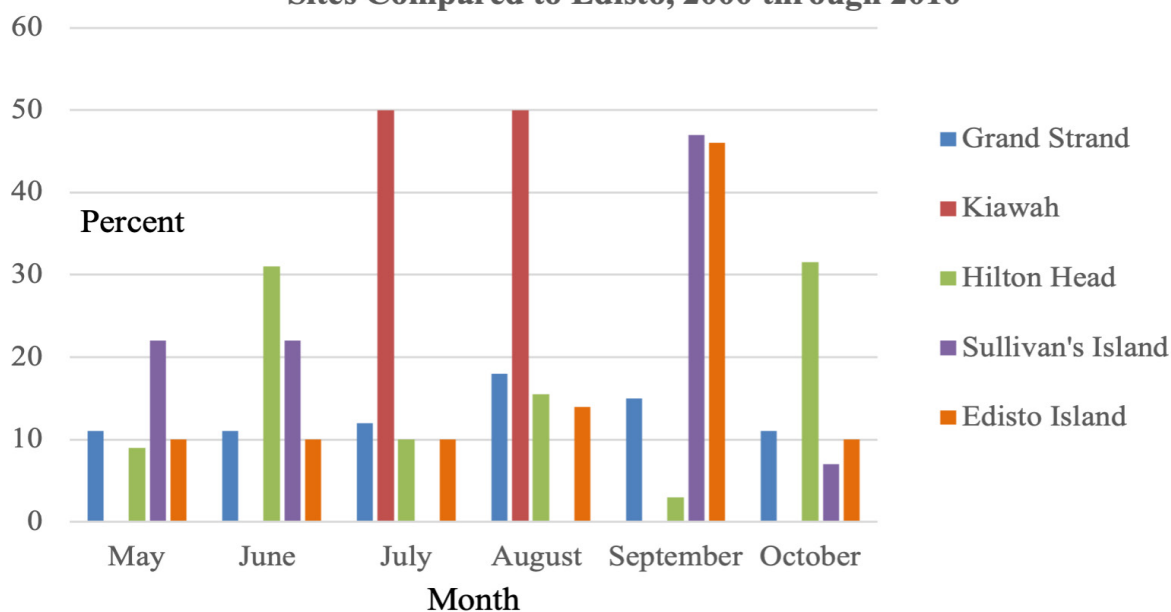


Figure 6. Comparison of the percentage of SSM contraventions at Edisto island and other major tourist destinations in SC from 2000 to 2016. Myrtle Beach and Grand Strand were relatively consistent across the time period from May to October. Hilton Head had the highest SSM contraventions during June, while Kiawah Island had only two SSM contraventions during June and August. Edisto Island and Sullivan's Island had similar patterns of Enterococci SSM contraventions occurring primarily in September.

DISCUSSION

Rapid increases in coastal populations and tourism may increase the risk for significant air and water pollution, as well as loss of biodiversity and wildlife habitat (Chenier et al. 2012). Climate change may impact the frequency and intensity of hurricanes and other severe rainfall events and may increase sea-level rise, all of which contribute to coastal flooding (Intergovernmental Panel on Climate Change 2009, 2014). For example, in Charleston, South Carolina, the number of extreme flooding events has increased substantially from 2 per year in the 1970s to over 40 events per year in 2018 (Union of Concerned Scientists 2014). Predictions for 2030 indicate that there will likely be 70 major flooding events per year, and for 2050 there may be nearly 180 events per year (Union of Concerned Scientists 2014). In 2019 there were 89 major flooding events in Charleston, SC (NOAA National Weather Service 2020) suggesting that sea-level rise is already occurring and perhaps at a faster rate than anticipated. Increased coastal flooding will mobilize more land-based pollution sources into coastal waters and hence increase the pollution of waterways used for contact recreation and fishing (Hartel et al. 2005, 2007; McDonald et al. 2006). High bacterial counts in coastal waters from this increased microbial pollution loading from both human and animal sources are likely to occur. Ecosystem services such as swimming and fishing may be negatively impacted as a result.

Results from this study indicated that the bacterial water quality on swimming beaches at Edisto Island only exceeded water quality criteria for *Enterococcus* bacteria SSM (104 MPN per 100 ml) 2.6 percent of the time from 2000 to 2016. Stations closest to Big Bay Creek, including LC-080A, LC-081, and LC-082, were the most impaired stations, having exceeded the SSM standards more often than any other stations. Rainfall did not appear to be strongly correlated with many of these observed Enterococci SSM contraventions. Although Hurricane Matthew and associated rainfall struck Edisto Island in October 2016, none of the *Enterococcus* MPNs in that year exceeded the SSM. This may be related in part to the increased rainfall that may co-occur with coastal flooding. Rainfall may have diluted bacterial pollution, as Enterococci levels only ranged from 0 to 20 MPN/100 ml. Deeb et al (2018) observed similar effects on *Vibrio* abundances in Winyah Bay, South Carolina, during the passage of Hurricane Sandy as the water volumes increased due to both rainfall and more tidal flooding, which then diluted *Vibrio* bacterial abundances in water samples. Tidal flooding during fair weather will not have this additional rainfall dilution effect often observed in major storm events, which may allow for localized contraventions of Enterococci bacterial pollution standards at locations with major concentrations of wildlife and pets (birds and dogs).

Microbial source tracking (qPCR) at stations near Big Bay Creek indicated that the primary bacterial pollution sources were birds and dogs. Other sources, such as other wildlife or humans, were not indicated by the results. Resident shore bird populations use beach areas for daily foraging and often defecate on beaches, which results in a bacterial pollution load that may affect water quality. Studies of beaches in Georgia have found that high levels of *Enterococcus* were observed in dry weather periods and were primarily related to bird pollution sources mobilized during flooding events (Hartel et al. 2005, 2007; McDonald et al. 2006). Many species of birds in this area are permanent residents, including the belted kingfisher, anhinga, seagulls, marsh hen, ruby-throated hummingbird, and wild turkeys. Tourists using beaches in the area often feed shore birds, which may add to the waste load through additional defecation. In addition, migratory waterfowl (e.g., royal terns, loons, pelicans, and northern parulas) may also fly through Edisto Island on annual migration routes during certain times of the year, adding to the endemic waste load from permanent bird populations within the area. Reptiles such as alligators and turtles may also contribute significant bacterial waste load in coastal areas (Johnston et al. 2010). Although alligators and turtles are both ectothermic, Enterococci may also occur in their intestines (Johnston et al. 2010). Although qPCR is not specific for bacteria from various types of dogs, it is possible that some of the Enterococci may have come from wild canids, such as coyotes, an invasive species on Edisto Island. The microbial source tracking was limited to stations only on the southern and western end of the island; however, these stations accounted for the majority (90%) of Enterococci SSM contraventions. Obtaining source tracking data from other Edisto Island beach monitoring stations with high Enterococci MPNs would help to further examine microbial tracking on Edisto Island.

Environmental factors such as rainfall, wind direction, tidal stage, and tidal height were analyzed on the dates when SSMs exceeded 104 MPN/100 ml for *Enterococcus* bacterial standards. Rainfall was negatively correlated with levels exceeding SSM standards. Rainfall amounts on the dates (+/- 24 hours) of the highest *Enterococcus* levels were ≤ 0.03 inches. Some factors occurred predominantly on dates of SSMs exceeding both 104 MPN/100 ml and 500 MPN/100 ml. These factors included time (occurrences in September), wind direction, tidal stage, and tidal height. This pattern suggests that increased tidal flooding from King Tides associated with sea-level rise and climate change, although not specifically analyzed, may be significant factors causing the SSM *Enterococcus* standard. From 1953 to 2020, a total of 197 King Tide events were measured in Charleston, SC, (NOAA National Weather Service 2020). From 1953 to 1990, there were only 23 King Tide events (11.7%) compared to 174 King Tide events (88.3%) from 1991 to 2020, with Sep-

tember being the month with the most events—41 (20.8%) (NOAA National Weather Service 2020). Seasonal peaks in Enterococci levels indicated that birds and dogs were the major sources of pollution in the Big Bay Creek area during September when higher tidal elevations inundate more of the beach face and beach habitat, loading higher quantities of their waste into surface waters used for contact recreation, such as swimming, to levels that often exceed water quality standards (10% of all samples collected in September from all stations were above the SSM).

The Ashepoo-Combahee-Edisto (ACE) estuary basin is a National Estuarine Research Reserve for NOAA and is much less developed than the Charleston Harbor basin (Grant et al. 2001). The lack of rapid permanent growth may partly explain why Enterococci levels have exceeded 104 MPN/100 ml only 50 out of 1,922 times (2.6%) in the last 15 years on Edisto Island. Although the correlation coefficient for the number of tourists versus the frequency of contraventions on Edisto was weak and negative, the data was limited. The moderately strong relationships between population density and Enterococci values indicated the importance of coastal population growth in increased risk of pollution. Myrtle Beach, Kiawah Island, Hilton Head Island, and Sullivan's Island are also major tourist beach destinations that have much higher population densities than Edisto Island, yet only Myrtle Beach and Sullivan's Island have a higher percentage of Enterococci SSM contraventions than Edisto Island. The burgeoning tourist industry has likely had an impact on increasing the sources of Enterococci contamination, as more visitors bring their dogs along for vacations (Edisto Chamber of Commerce 2017). More data from Edisto and other South Carolina coastal communities would likely yield stronger relationships. Dogs may contribute to pollution during beach activities if owners do not adequately clean up their waste. Most of the SC beaches significantly restrict dog access during the peak of tourist season. Edisto Island is an exception, as dogs are allowed direct beach access 24 hours a day throughout the year. Similarly, Sullivan's Island allows dog access by permit for residents. It is interesting to note that these two dog-friendly beaches are ranked just behind Myrtle Beach for the most frequent contravention of Enterococci SSM standards, and the majority of the contraventions occur during September when King Tides are most frequent. Similarly, shore birds on Edisto Island are drawn to the public on beaches that will feed the birds, often leading to increased defecation directly on the beach (Schoen et al. 2010). Although microbial source tracking data is not available for other beaches such as Kiawah Island and Hilton Head for the time period studied, pollution sources would likely differ at these other locations due to greater restrictions on tourist activities.

The primary sources of pollution on Edisto Island as indicated by qPCR results are from birds and dogs. These

additional pollution sources may inundate coastal areas due to increased occurrence of King Tides associated with increased sea-level rise. The most frequent Enterococci SSM contraventions (70.4%) occurred during September when King Tides are most frequent; similar patterns may exist for other fecal indicator bacteria. Cows, pigs, horses, and ruminant bacteria were not detected, nor were human sources identified in our microbial source tracking analysis.

People do not consistently clean up after their dogs when visiting the beach, despite availability of equipment throughout the island beaches. Many visitors are also attracted to feeding birds on the beach. These known microbial pollution sources need to be addressed now as evidence from this study strongly suggests that increased coastal flooding is inundating a larger portion of the beach face. The flooding washes pollution from these sources onto beaches used for contact recreation, such as swimming. Although the current research utilized data from multiple stations on Edisto Island, future research could include greater sample sizes as well as longer time periods to determine trend analysis. Analysis other than correlation coefficients could therefore be obtained to better determine the associations between fair weather flooding, rainfall, tourism numbers, and population density. Civic leaders can begin by providing more public education messaging with realtors, residents, and tourists to inform the public that cleaning up after dogs and not feeding birds is important to maintaining recreational water quality on Edisto Island. Future policies on feeding birds and dog cleanup enforcement will need to be developed to reduce these sources of microbial pollution on Edisto Island to keep the beaches safe for contact recreation in the future.

CONCLUSION

Water quality on Edisto Island was studied to better identify causes of water quality impairments on beaches used for contact recreation. While the permanent population growth has been relatively slow on Edisto Island, a rise in tourism has resulted in a significant increase in the number of visitors who use the many amenities of the island. Edisto Island is one of the more dog-friendly beaches in South Carolina, and tourists often feed birds on local beaches, and microbial source tracking indicated that birds and dogs were the major bacterial sources affecting contact recreation through beach closures. Multiple factors appear to contribute to bacterial contamination that affects the water quality of bathing beaches on Edisto Island. Rainfall was negatively correlated with SSMs exceeding 104 MPN/100 ml, and rainfall amounts on the dates (+/- 24 hours) of peak *Enterococcus* levels were < 0.03 inches per day. Although rainfall per se did not appear to directly impact Enterococci levels, time (September), wind direction, tidal stage (flood tide), and height significantly ($p < 0.05$) correlated with bacteria levels. High Enterococci levels

threaten recreational use through beach closures, and most of the highest bacterial counts occurred in September, the peak time for King Tides often associated with sea-level rise and climate change (Pietrafesa et al. 2015). These analyses suggest that seasonal peaks in Enterococci levels results from greater inundation of bird and dog waste particularly in the Big Bay Creek area during September when higher tidal elevation inundate more of the beach face and beach habitat, loading larger quantities of waste into surface waters used for contact recreation to levels that often exceed water quality standards (10% of the time). Measuring the upstream area of Big Bay Creek would further assist in microbial source tracking.

Containment of pollution could help restore ecosystem services on Edisto Island, especially the southwestern portion of the island where Big Bay Creek is situated. However, increasing frequency and magnitude of King Tides and sea-level rise and resulting coastal flooding are expected in the future. This will likely cause even greater areas of bird, wildlife, and dog waste to be inundated and likely increased microbial loading to areas used for contact recreation. Tourists and residents alike can manage dog sources through programs that enforce the removal of dog waste from beaches that are likely to flood. Similarly, restrictions on feeding birds on beaches would further reduce these identified sources of bacterial pollution on Edisto Island in the future.

Comparisons of Edisto Island *Enterococcus* violation rates with other South Carolina beach areas indicated that Edisto Island has a lower rate of contraventions than Myrtle Beach, Grand Strand, and Sullivan's Island but more contraventions than Hilton Head Island and Kiawah Island. Further research should analyze results from these other South Carolina beach locations to better understand future bacterial pollution loadings from increasing King Tides and sea-level rise. As population growth and tourism in coastal areas continues to increase, ecosystem degradation and loss of ecosystem services such as the ability to swim will continue to become more threatened. Understanding the increased potential in mobilization of bacterial pollution sources of contamination on Edisto Island and other coastal areas due to fair weather tidal flooding associated with sea-level rise will help policy makers and researchers achieve their collective goal of providing clean water for residents and tourists visiting the coast.

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Widespread Contamination of Polychlorinated Biphenyls in South Carolina and North Carolina (USA): A Legacy of Malarial Eradication and Mosquito Control

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Abstract. The South Carolina Department of Health and Environmental Control (SCDHEC) has been conducting fish tissue monitoring for Polychlorinated Biphenyls (PCBs) since 1974 and, based on the results, restrictive fish consumption advice has been in place at two reservoirs in South Carolina for several decades. But in 2009, widespread contamination was reported in fish from the Catawba-Wateree and Yadkin-Pee Dee River Basins. Therefore, beginning in 2010, additional monitoring of fish tissue for PCBs in the rivers and reservoirs of these two basins was initiated. Results from a spatial analysis, combined with evidence from historic literature, suggests that the source of the PCB contamination, in part, is from past direct application of used transformer oil on reservoirs located along the two rivers, the origins of which were hydroelectric projects in both basins. The use of used motor oil for mosquito control and malaria eradication was widespread in the first half of the twentieth century, and results suggest that for some utility operations, PCB oil was utilized to augment these programs. The global ramifications of these findings are not yet known, but they should encourage reconsideration of origin, transport, and fate of PCBs in other regions, particularly where a known source of environmental contamination is not obvious.

INTRODUCTION

Polychlorinated Biphenyls (PCBs) were discovered in the late 1880s with commercial production by the company Monsanto beginning in 1927 (Cairns et al. 1986). Because they are chemically stable, are of low flammability, and are poor conductors of electricity they had many industrial applications, especially as a cooling oil for electric transformers and capacitors. They were also widely used in paints and resins, carbon paper production, and hydraulics. The toxicity of PCBs to humans was acutely seen when families in Kyushu, Japan, exhibited disfiguring dermatitis and liver and kidney damage after consuming PCB-contaminated rice oil (Saeki et al. 1971). PCBs are considered a probable human carcinogen by the US Environmental Protection Agency (EPA), and US production ceased in the late 1970s (Eisler 1986). However, because of their chemical stability and widespread use, PCBs remain in the environment and continue to be found in elevated levels in soil and in the tissue of fish and other animals.

Structurally, PCBs were produced by the chlorination of biphenyl rings resulting in 209 possible configurations, which

are generally referred to as congeners. These congeners can be grouped based on the number of chlorine atoms, regardless of position, into 10 possible classes called homologs (e.g., tetrachlorobiphenyls). Aroclor was the brand name given to PCB mixtures by the company Monsanto, which produced most of the PCBs in the United States (Cairns et al. 1986). The trade name Aroclor was followed by a four-digit numeric value (e.g., Aroclor 1260), with the first two digits indicating the number of carbon atoms and the last two indicating the approximate percentage, by mass, of the chlorine content.

South Carolina waterways are ecologically diverse, containing mountainous, piedmont, and coastal ecoregions (Griffith et al. 2002). Many waterways are self-contained within the boundaries of the state while some originate in, or are shared by, Georgia, North Carolina, and a small portion of Virginia. Historically, the state of South Carolina has issued fish consumption advisories due to the presence of contaminants in these waterways. There are four distinct regions of South Carolina that contain levels of PCBs in fish tissue that resulted in restrictive consumption advice being issued (SCDHEC 2021) (Figure 1). These regions are Lake

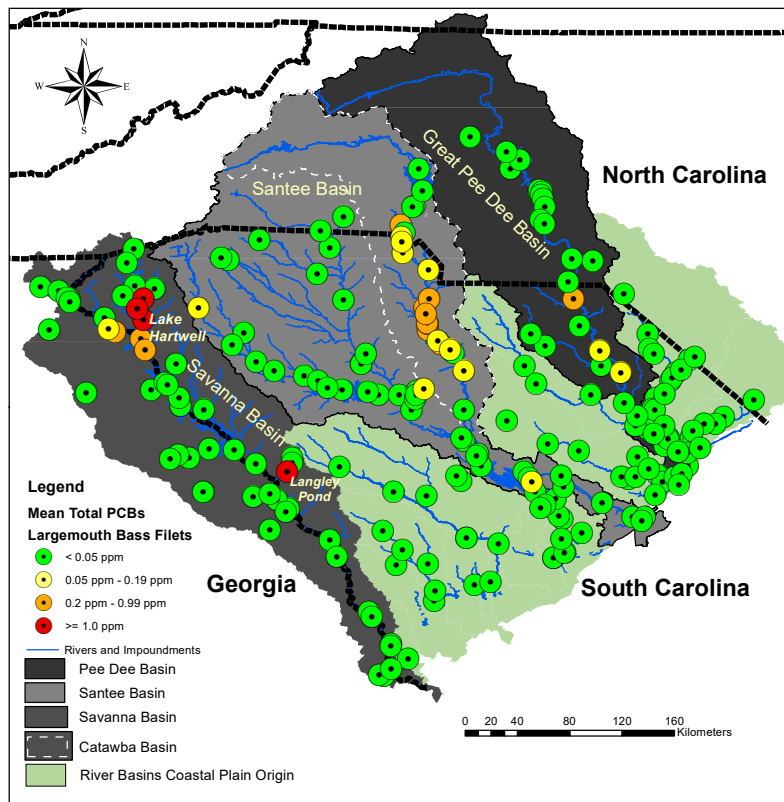


Figure 1. Mean total PCBs (ppm wet weight) in largemouth bass filets from waters of South Carolina, showing major drainage basins of the state.

Hartwell in northern SC, Langley Pond in Aiken County SC, the Catawba River Basin, and the Great Pee Dee River Basin.

The first report of PCBs in biota of South Carolina was from Lake Hartwell, Pickens County, in 1976 (Bruner and Hill 1977; Aldridge 1978). The source of this contamination was an industrial discharge that emptied into Twelve Mile Creek, which entered Lake Hartwell a short distance downstream. Since then, significant research has been conducted on PCB contamination in this region, and in 1990 the Sargamo Operable Unit Two, the point of contamination, was finalized on the National Priorities List (US EPA Superfund) (Gaymon 1992a). Elevated levels of PCBs in fish tissue were also reported from Langley Pond, Aiken County, South Carolina (Darr 1986). This reservoir was created in the late 1800s and received large amounts of industrial waste, mostly from textile plants, for nearly 100 years. In more recent years, widespread PCB contamination was also discovered in two large river basins of the Carolinas. Fish from the Catawba/Wataree Basin and the Great Pee-Dee/Yadkin Basin have been found to contain levels of PCBs to warrant both South Carolina and North Carolina issuing restrictive consumption advice for certain fish species (SCDHEC 2021; NCDHHS 2021). The rivers and reservoirs of the Catawba/Wataree and the Great Pee-Dee/Yadkin Basins are the focus of this paper.

Low but detectable levels of PCBs were first reported from whole fish samples from the Catawba River Basin in the 1970s (Aldridge 1978). While the Great Pee Dee River was monitored, no detectable levels of PCBs were reported at that time. PCBs were again reported from fish collected in 1986 from a large reservoir, Lake Marion, located downriver from the Catawba River (Marcus 1987). The first large-scale investigation of PCBs and other contaminants in Catawba River fish was conducted by the Duke Power Company in 1993 (Coughlan 1995). Largemouth bass filets were collected from 26 different locations in both North Carolina and South Carolina, most from reservoirs managed by Duke Power in both states. In this study PCBs were not detected in largemouth bass filets; however, the detection limits of 0.28 ppm to 0.35 ppm for Aroclor 1260 were much higher than the 0.05 ppm detection limits reported by Aldridge (1978) and Marcus (1987). These detection limits were also much higher than the initial threshold that triggers limited fish consumption advice by the SCHDEC and the North Carolina Department of Health and Human Services (NCDHHS).

Beginning in 1999, the US EPA (2009a) conducted a national probabilistic fish contaminant study of lakes and reservoirs in the US. The results of the study were summarized in a national report in 2009, which revealed PCBs con-

tamination in fish collected from several reservoirs on the Catawba River. This rediscovery of PCBs in South Carolina fish brought renewed awareness of the problem, leading the SCDHEC and the North Carolina Department of Environmental Quality (NCDEQ) to conduct additional monitoring of this basin. The results led to the issuance of restrictive consumption advice for several fish species from the Catawba River chain of reservoirs and certain portions of the river by the SCDHEC and the NCDHHS. Not long after these findings, PCBs were found in fish from the upper Great Pee Dee River in South Carolina. Near this time, the NCDEQ was investigating PCBs in several reservoirs in the Yadkin/Pee Dee Basin, with an Alcoa Plant located on Badin Lake considered a possible source (NCDHHS 2009; Mort 2017). In South Carolina, restrictive fish consumption advisories were already in place for the Great Pee Dee River because of mercury, but the discovery of PCBs prompted an investigation into possible sources for widespread contamination in fish from both the Catawba and Pee Dee Basins. Therefore, the primary objective of the study presented here was to investigate and determine the probable source or sources of PCB contamination in the Great Pee Dee/Yadkin River Basin and the Catawba/Wateree Basin. A secondary outcome of the study was a characterization of the spatial trends of PCBs in fish of South Carolina, including those from waterways that are shared with Georgia and North Carolina.

MATERIALS AND METHODS

DESCRIPTION OF STUDY AREA

Figure 1 shows the area of study as we conceived it, showing a portion of Georgia that shares the Savannah River Basin with South Carolina and the portions of North Carolina. In addition to the Savannah River, the Great Pee Dee River and Santee River Basins are large Atlantic drainages with headwaters that originate in the Blue Ridge Mountains. There are also many smaller basins self-contained within the political boundaries of South Carolina, all of which originate in or near the coastal plain of the state. Highlighted in Figure 1 is the Catawba River Basin, an upper section of the Santee River Basin. Lake Hartwell and Langley Pond, in which high levels of PCBs have occurred for many years, are labeled and sampling sites are indicated with red points. All the waters of South Carolina, whether self-contained or shared, meander through the landscape of the state and empty into the Atlantic Ocean. Except for the Savannah River, the Atlantic terminus of which is shared with Georgia, the confluence of these waterways with the Atlantic occurs completely within the boundaries of South Carolina.

Like much of the United States below the historic glacial line, South Carolina lacks large lakes and very few, small, natural, lentic waterways. However, over the past 150 years, numerous large and small dams have been erected across riv-

ers and streams, which are referred to by various terms such as lakes, reservoirs, impoundments, and ponds. No large reservoirs, defined as greater than 50 feet in dam height, existed in South Carolina in 1850, but by 1987 there were 92 (US ACE 2021). These dams were mostly erected beginning in the 1900s for various purposes including hydroelectricity production, flood control, drinking water sources, and a source for industrial cooling water. In most cases, over time, they also became important for recreation, with permanent and secondary homes being constructed along their shores. One of the more extensively modified rivers in the Carolinas is the Catawba River, with many hydroelectric reservoirs constructed on the river by what is now Duke Energy. There are 11 such large impoundments on the Catawba, which extends from Lake James in North Carolina to over 400 km downriver to Lake Wateree in South Carolina (Table 1). The Yadkin/Pee Dee River also has several hydroelectric dams that were built in the early twentieth century (Table 1). A series of four reservoirs were constructed beginning in 1917 by the Tallahassee Power Company and Alcoa Corporation. For many years these were owned and operated by the Alcoa Corporation, but in 2017 they were acquired by Cube Hydro Carolinas, LLC (Cube Hydro 2021). Between the lowermost point of these reservoirs and the point where the Great Pee Dee River crosses into South Carolina there exists Lake Tillery and Blewett Falls Reservoir. Originally operated by Carolina Power and Light, these two projects are now owned and operated by Duke Energy. Table 1 shows water bodies in the study area where restrictive fish consumption advisories have been issued by the SCDHEC, the NCDHHS, and the GADNR because of PCBs, which were current at the time of this writing.

FISH COLLECTION AND PROCESSING

Glover et al. (2010) and the SCDHEC (2001) described methods utilized in the collection and processing of fish tissue in South Carolina. This involves the collection of fish using standard electroshocking techniques at public water bodies in South Carolina (US EPA 2000a). Largemouth bass were targeted at all sites while certain other species were collected when present, particularly game fish that may be an important part of the local fishery. Specimens were placed on ice and returned to the laboratory where they were processed individually. Standard measures were recorded and a skin-on, scale-off fillet was utilized for most species. For catfish species, skin-off fillets were taken. Using standard US EPA (2000a) methods, fillets were homogenized with dry ice and delivered to the SCDHEC laboratory for analysis.

Fish samples from other agencies, including those from the US EPA, Georgia, and North Carolina, utilized similar collection techniques. More details on specific collection and processing methods can be found in NCDENR (2013) for the state of North Carolina, in Georgia Department of

Table 1. Fish Consumption Advisories for PCBs in Select Basins in South Carolina

Basin	State	Reservoir	Year Built	Fish Consumption Advisory—PCBs*
Catawba	NC	Lake James	1923	No
Catawba	NC	Rhodhiss Res.	1925	No
Catawba	NC	Hickory Res.	1927	No
Catawba	NC	Lookout Shoals Res.	1915	No
Catawba	NC	Lake Norman	1963	STP, HYS (NCDHHS)
Catawba	NC	Mountain Island Res.	1924	BLC, CHC (NCDHHS)
Catawba	NC/SC	Lake Wylie	1904	LMB (NCDHHS); LMB, CHC, BKS (SCDHEC)
Catawba	SC	Fishing Creek Res.	1916	LMB, BLC, CHC, WHB, BKS (SCDHEC)
Catawba	SC	Great Falls Res.	1907	No
Catawba	SC	Cedar Creek Res.	1909	LMB, BLC, CHC, WHB, BKS (SCDHEC)
Catawba	SC	Lake Wateree	1920	LMB, BLC, CHC, WHB, STB, BKS (SCDHEC)
Pee Dee	NC	High Rock Res.	1927	Catfish all species (NCDHHS)
Pee Dee	NC	Tuckertown Res.	1962	No
Pee Dee	NC	Badin Lake	1917	LMB, Catfish all species (NCDHHS)
Pee Dee	NC	Falls Res.	1919	Catfish all species (NCDHHS)
Pee Dee	NC	Lake Tillery	1928	Catfish all species (NCDHHS)
Pee Dee	NC	Blewett Falls Res.	1912	No
Savannah	SC/GA	Lake Hartwell	1959	All Species (SCDHEC); LMB, CHC, STP, HYS (GADNR)
Savannah	SC	Langley Pond	1870	All Species (SCDHEC)

Note. LMB = largemouth bass, HYS = hybrid striped bass, BLC = blue catfish, CHC = channel catfish, BKS = black crappie, WHB = white catfish, STP = striped bass. *No Advisory generally because of lack of data rather than absence of tissue PCBs.

Natural Resources (1992), in US EPA (2000b) for the USEPA National Lakes Study, and in US EPA (2016) for the US EPA Catawba Indian Nation special study.

FISH TISSUE DATASETS

The SCDHEC data served as the primary data source for the state and included fish tissue fillets collected beginning in 1991. Watersheds shared by the two Carolinas include Santee (which contains the Catawba/Wateree), Yadkin/Pee Dee, Little Pee Dee/Lumber, and Waccamaw. For the portions of these watersheds outside of South Carolina, data were provided by the North Carolina Department of Environmental Quality (NCDEQ) in partnership with the North Carolina Department of Health and Human Services (NCDHH). The states of Georgia and South Carolina share the Savannah River Basin, and data collected by the Georgia Department of Natural Resources (GADNR) were also used in this study. A national study on fish tissue contamination was conducted by the US EPA (2009a) in the late 1990s and early 2000s. Of the 500 lakes sampled across the United States, 10 were contained within or flowed into South Carolina. In support of the Catawba Indian Nation, fish tissue PCB data were also obtained by the US EPA (2016) from the Catawba River. Data for largemouth bass fillets from Coughlan (1995)

for the Duke Power reservoirs were not used in our analysis because there were high detection limits for Aroclors in that study (0.28 ppm–0.35 ppm). The combined datasets represent 2,075 individual or composite samples analyzed for PCBs and 4,232 fish specimens. There were 44 different species collected and processed from 303 different sampling locations from 1991 to 2016. The dominant species was largemouth bass, with 46% of all samples represented by this species. Channel catfish were the second most dominant species, representing 10.7% of the samples. This large volume of data, over space and time, allowed for a comprehensive assessment of PCBs in fish from the waters of South Carolina and provided insight into possible sources.

For analysis and reporting and display, we used total PCBs reported in parts per million (ppm) wet weight. We report wet weights because most of the data used for this study were only available in this format due to its use for determining fish consumption. To compute total PCB levels for each fish or fish tissue composite sample, individual congeners or Aroclors were summed for each sample. For reporting and display we used the mean of total PCBs for samples from a specific sampling point. EPA methods 8082 and 1656 were utilized for Aroclor analysis of fish tissues, while EPA method 1668 was used for congener-specific anal-

ysis of fish tissues. For additional information on standard operating procedures for laboratory tissue analysis, see SCDHEC (2012) for South Carolina, NCDENR (2013) and Mort (2017) for North Carolina, GADNR (1992) for Georgia, US EPA (2016) for Catawba Indian Nation Special Investigation, and US EPA (2000c) for the US EPA national study on lake fish tissue.

To compare the many samples for which Aroclor-only data were available (mostly in SC) with those sites with congener-only data (in NC), PCB congeners were summed and grouped into their homolog class and then converted to a percentage for each homolog for a given sample. The Agency for Toxic Substances and Disease Registry (ATSDR 2000) listed the approximate composition of each Aroclor as expressed in homolog percentages. For example, Aroclor 1260 was shown to be dominated by hexachlorobiphenyls, while pentachlorobiphenyls are the dominant component of Aroclor 1254. We used the percent homologs for each sampling site and a given species of fish to approximate the most probable Aroclor composition, which allowed sites at some North Carolina reservoirs to be compared to those in South Carolina. We did this for the congener data from the EPA national fish tissue study (US EPA 2009a), although both Aroclor and congener data were analyzed for all fish in this project. Having both Aroclors and congeners for the same sample allowed for additional insight into the extrapolation of Aroclors from congener data.

SPATIAL ANALYSIS

Spatial analysis and display were performed with Esri ArcView 10 (2020). Important data layers included the National Hydrography Dataset, the National Landcover Dataset, and in-house layers created by the SCDHEC, such as fish tissue monitoring locations. For many of the figures presented here, sample sites are represented as points on maps, and colors represent levels of PCBs that correspond to the thresholds that trigger a consumption advisory by the SCDHEC (2021). These categories are “no restrictions” of consumption (<0.05 ppm, Green), “eat no more than one meal per week” (0.05 ppm to 0.19 ppm, Yellow), “eat no more than one meal per month” (0.2 ppm to 0.99 ppm, Orange), and “do not eat any” (≥ 1.0 ppm, Red). Because consumption advisories are given for water bodies and not points, these figures are not intended to represent an advisory but rather to represent spatial trends. Further, the states of Georgia and North Carolina have slightly different means and methods for issuing fish consumption advisories than South Carolina, making this scale not as relevant for these states. However, the first trigger for issuing restrictive consumption advisory in all three states is fish tissue PCB levels of 0.05 ppm or above. Fish consumption advisories for South Carolina, North Carolina, and Georgia may be found at SCDHEC (2021), NCDHHS (2021), and GADNR (2021), respectively.

Largemouth bass filets were well represented in the dataset across space and time and served as a good surrogate for spatial trends. Channel catfish and blue catfish filets were also used to evaluate trends, especially where largemouth bass were absent. To provide a more robust spatial coverage and increase sample size, these two catfish species were combined to examine trends. We could not confidently assess temporal trends because of insufficient data over time at specific sample locations.

STATISTICAL ANALYSIS

Testing for differences of PCBs for point data was not possible due to small sample sizes at many locations. To increase sample size, multiple sample sites at individual bodies of water were combined. Tests for differences in PCB levels in largemouth bass in the Catawba River Watershed were conducted for 7 waterways (Mountain Island Reservoir, Lake Wylie, Catawba River, Fishing Creek Reservoir, Cedar Creek Reservoir, Lake Wateree, and Wateree River). Lake Norman was not included in this analysis due to small sample size ($n = 2$). For catfish, 8 groups were evaluated, which included the above water bodies and Lake Norman. For the Great Pee Dee Watershed, 5 groups were evaluated for both largemouth bass and catfish (High Rock Reservoir, Badin Lake, Falls Reservoir, Lake Tillery, and the Great Pee Dee River in South Carolina). To test for assumptions of normality, Q-Q plots were constructed and Shapiro-Wilk Tests for normality were conducted. For the Catawba River Watershed, both for largemouth bass and catfish, the data were not normally distributed. The nonparametric Kruskal-Wallis Test was thus used, and the post hoc Dunn's test was used to determine which groups differed. For both largemouth bass and catfish data in the Great Pee Dee Watershed, data were found to be normally distributed, and ANOVA tests were used to test for differences in groups. For ANOVA, the post hoc Tukey-Kramer test was used to compare groups. The accepted level of significance for all tests was $p < 0.05$. The data analysis for this paper was generated using the Real Statistics Resource Pack software (Release 7.6) (Zaiontz 2020).

RESULTS

Figure 1 shows the spatial distribution of total PCBs in largemouth bass filets from waters of South Carolina to include those shared with Georgia and North Carolina. Mean total PCB values for largemouth bass filets ranged from below detection (< 0.05 ppm) to 6.4 ppm at a site on Lake Hartwell in South Carolina. Of the 171 SCDHEC sampling locations with largemouth bass fillet data, 15% had mean total PCB levels greater than or equal to 0.05 ppm. Of the 145 points in Figure 1 shown in green (mean total PCBs <0.05), 94% had no detectable PCBs found in any of the fish samples analyzed for Aroclors. The maximum value

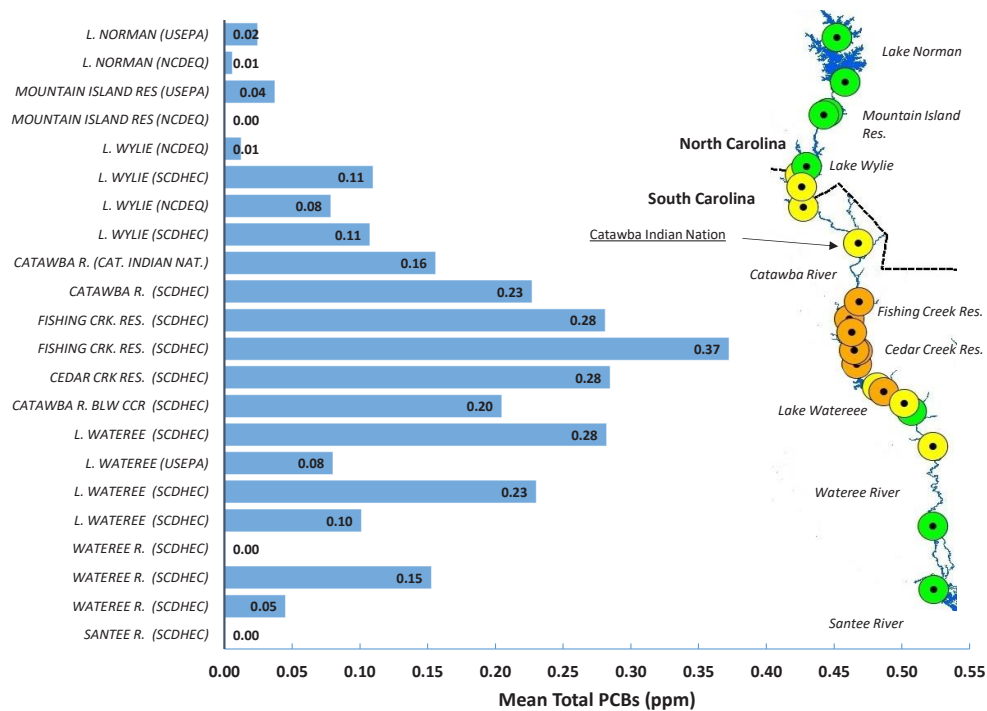


Figure 2. Mean total PCBs (ppm wet weight) in largemouth bass fillets from the Catawba River Basin of the Carolinas (means labeled on each bar). Mean total PCBs for green points <0.05 ppm, yellow points 0.05–0.19 ppm, and orange points 0.20–0.99 ppm.

for a largemouth bass fillet sample was 19.7 ppm, a site on Lake Hartwell in South Carolina, and the maximum mean total PCBs for largemouth bass fillets (n=49 samples) was 6.4 ppm, from a different sampling site on this same reservoir. PCBs in fish tissue at levels that have triggered consumption advisories have been found in four areas: Lake Hartwell (SC/GA), Langley Pond (SC), the Catawba/Wateree River Basin (SC/NC), and the Yadkin/Pee Dee River Basin (SC/NC) (see Table 1 and Figure 1). Shown also as yellow points in Figure 1 are three additional locations where mean PCB levels exceeded 0.05 ppm for largemouth bass fillets, which included Sesquicentennial State Park Lake, a small reservoir in the center of the state, the Saluda River in the western part of South Carolina, and a site toward the coast on the Santee River directly below the dam on Lake Marion. However, these three sites had small sample sizes of individual fish (5, 3, and 2 respectively), and their means were elevated because of a single specimen at each location. Additional data are needed to determine any real trends, and at this time consumption advisories for PCBs have not been issued for these water bodies (SCDHEC 2021).

LAKE HARTWELL AND LANGLEY POND

The highest levels of fish tissue PCBs occurred in Lake Hartwell and Langley Pond, with readings well above 1 ppm mean total PCBs in the fillets of many fish species (Figure 1). Both locations have a long history and record of PCB

contamination, and remediation efforts have occurred at both (US EPA 2009b; CH2M Hill Engineers 2016). The source of PCBs in Lake Hartwell was a chemical plant on Twelve Mile Creek, which drains into the lake. Langley Pond was constructed in 1870 as an impoundment of Horse Creek. Large numbers of textile mills occurred in this watershed, releasing industrial waste into the creek for decades, which settled into this downstream impoundment. A complete evaluation of these two sites is beyond the scope of this paper, but further information can be found in other studies (Bruner and Hill 1977; Aldridge 1978; Marcus 1987; Gaymon 1992b; Darr 1986; US EPA 2009b; CH2M Hill Engineers 2016).

CATAWBA/WATEREE WATERSHED

The pattern of PCBs in fish tissue in the Catawba/Wateree Basin is illustrated in Figures 1 through 4. PCBs were present in largemouth bass fillets in Lake Norman and Mountain Island Reservoir, North Carolina, but at relatively low levels (mean total <0.05 ppm). Higher levels (mean total >0.05 ppm) were found in fish from Lake Wylie at the North Carolina-South Carolina border. In South Carolina values were still higher in the Catawba River near the Catawba Indian Nation, which is below the confluence of Sugar Creek. The headwaters of Sugar Creek are in North Carolina, and much of the city of Charlotte occupies this watershed. Levels consistently exceeded 0.2 ppm at Fishing Creek Reservoir and remained elevated in Cedar Creek Reservoir just

downriver. The highest mean PCB levels in largemouth bass fillets for the basin were 0.37 ppm at a site on Fishing Creek Reservoir (n=22 samples) (Figure 2). While PCB values were obtained by several agencies utilizing different laboratories and methods (Aroclors vs. Congeners), the patterns were remarkably consistent for total PCB tissue levels throughout the watershed.

The Kruskal-Wallis test indicated that some waterways in the Catawba Basin were significantly different for mean PCB concentrations in both largemouth bass and catfish fillets ($H=42.7$, $p < 0.001$) and catfish ($H=30$, $p < 0.001$) (Figures 3 and 4). Figure 3 shows the group differences for largemouth bass, with Cedar Creek Reservoir and Fishing Creek Reservoir having the highest levels of PCBs and Lake Norman, Mountain Island Reservoir, and Lake Wylie having the lowest. The post hoc Dunn's test showed that mean PCB values in largemouth bass were not significantly different in Lake Wylie and Mountain Island Reservoir, though these two reservoirs were, in general, significantly different ($p < 0.05$) from the others. An exception was that mean PCB levels in largemouth bass in Lake Wylie and the Wateree River were not significantly different ($z=0.87$, $p=0.38$). Figure 4 shows the results for PCBs in catfish from the Catawba River Basin. The patterns were similar between catfish and largemouth bass. The highest levels of PCBs were in fish from waterways beginning at the Catawba River in South Carolina, while they were lower in the 3 upriver reservoirs (Lake Norman, Mountain Island Reservoir, and Lake Wylie). While the patterns were similar for catfish and largemouth bass, results of the Dunn's post hoc test indicated that PCBs in catfish in the Catawba River, Fishing Creek Reservoir, Cedar Creek Reservoir, Lake Wateree, and the Wateree River were not significantly different from each other (Figure 4).

Though evaluations and reporting were conducted only on largemouth bass and catfish, consumption advisories have been issued for several species in these water bodies by the SCDHEC and the NCDHHS (Table 1).

Aroclor 1260 was the dominant PCB mixture in fish from the Catawba/Wateree Basin in both North Carolina and South Carolina (Figure 5). This included samples analyzed by the SCDHEC, the EPA's national fish tissue study (US EPA 2009a), the EPA Catawba Indian Nation special study (US EPA 2016), and the Aroclor samples processed by the NCDEQ. The homolog profile computed from the EPA national fish tissue study (US EPA 2009a) for Lake Norman, Mountain Island Reservoir, and Lake Wateree shows a composition that suggests Aroclor 1260, and strongly resembles that which was given by ATSDR (2000) (Figure 5). The Aroclor analysis for these same three sites and specimens, both for the fillets and whole fish (n=6 samples), showed 100% Aroclor 1260. This homolog profile suggesting Aroclor 1260 was similar to the profile seen in most fish species in the Yadkin River Reservoirs in North Carolina (Mort 2017) but dif-

ferent from the Aroclor analysis processed from the Great Pee Dee River in South Carolina, Lake Hartwell in South Carolina, and Langley Pond in South Carolina, all of which were reported as predominantly Aroclor 1254 (Figure 5).

YADKIN/PEE DEE WATERSHED

Figures 6 through 8 show the pattern of PCB contamination in largemouth bass and catfish fillets from the Yadkin/Pee Dee River Basin in North Carolina and South Carolina. PCBs are relatively low (<0.05 ppm) in fish from a series of reservoirs on the Yadkin River and the Great Pee Dee River in North Carolina near the state line. In the Great Pee Dee River in South Carolina the levels are substantially higher, with mean PCB levels in largemouth bass fillets at 0.26 ppm at station PD-012. There was a decreasing trend from this site moving downriver. Levels were above 0.05 ppm at PD-337 (n=5 samples), which was 74 km downriver of PD-012, but were low or below detection limits beginning at PD-622 (n=5 samples), which is 98 km downriver of PD-012. The ANOVA analysis indicated group differences in PCBs of largemouth bass in the Great Pee Dee River Basin ($F=4.7$, $p<0.01$). In general, this was driven by the high levels of PCBs in the Great Pee Dee River in South Carolina. The Tukey-Kramer Test indicated that reservoirs in North Carolina were not statistically different from each other ($p>0.05$), with the exception of Falls Reservoir, where significantly different levels were reported from the Great Pee Dee River in South Carolina.

Patterns were similar for catfish fillets as for largemouth bass in the Great Pee Dee Basin (Figure 8). However, PCBs for catfish were sufficiently elevated in some of the Yadkin Reservoirs in North Carolina to the point where the NCDHHS (2021) issued restrictive consumption advice for catfish. Group differences were significant (ANOVA $F=6.3$, $p<0.001$) and appeared to be driven by the high values in the Great Pee Dee River in South Carolina (Figure 8). However, means were not significantly different for Badin Lake and the Great Pee Dee River in South Carolina (Tukey-Kramer $q=2.7$, $p=0.33$).

Most PCBs from fish collected from stations on the upper Pee Dee River in South Carolina were reported as Aroclor 1254 (92%) (Figure 5). This was comparable to Langley Pond (97%). PCBs from fish in Lake Hartwell were also reported as mostly Aroclor 1254 (67%), but 29% were also reported as Aroclor 1260. This contrasts with the Catawba River Basin, where 95% of Aroclors were reported as 1260. However, the homolog profile for sites on the Yadkin Reservoirs in North Carolina was like those on the Catawba and suggests Aroclor 1260 as the dominant mixture in fish tissue from most locations. Mort (2017) reported similar results and provided a comprehensive evaluation of the homolog and congener patterns in the tissue of fish from these Yadkin reservoirs.

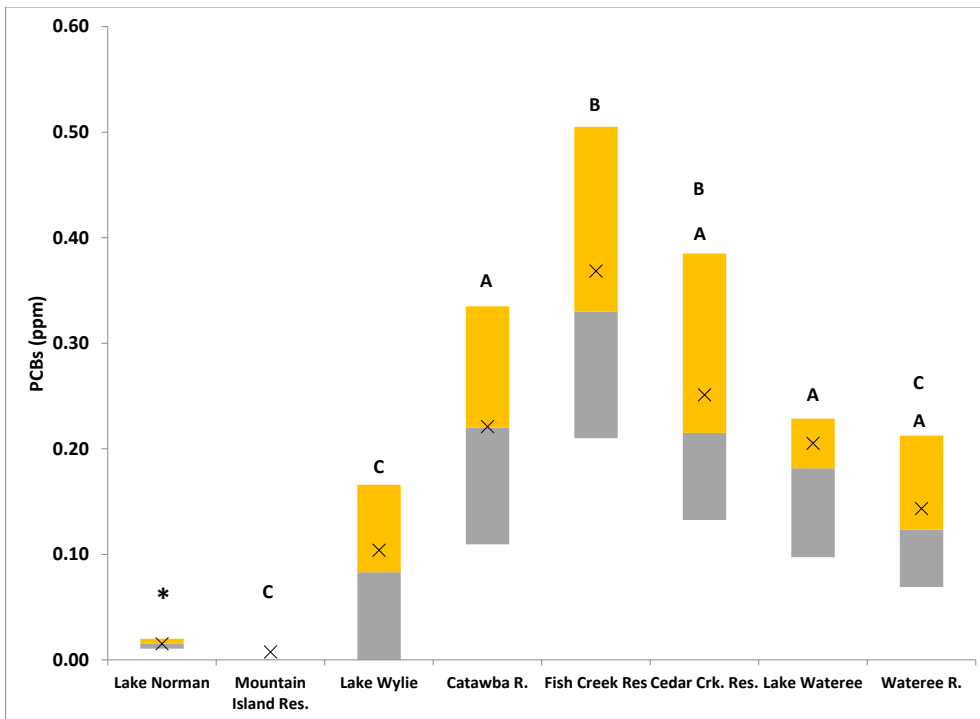


Figure 3. Box plot of PCBs in largemouth bass from water bodies in the Catawba River Watershed showing quartile 1 (bottom of grey columns), median (top of grey columns, bottom of yellow columns), quartile 3 (top of yellow columns), and mean (X). Group means were significantly different (Kruskal-Wallis Test $H=42.7$, $p < 0.001$). Groups with different letters were significantly different from each other ($p < 0.05$), while groups with the same letter were not significantly different (Dunn's post hoc test). *Not included in model due to low sample size.

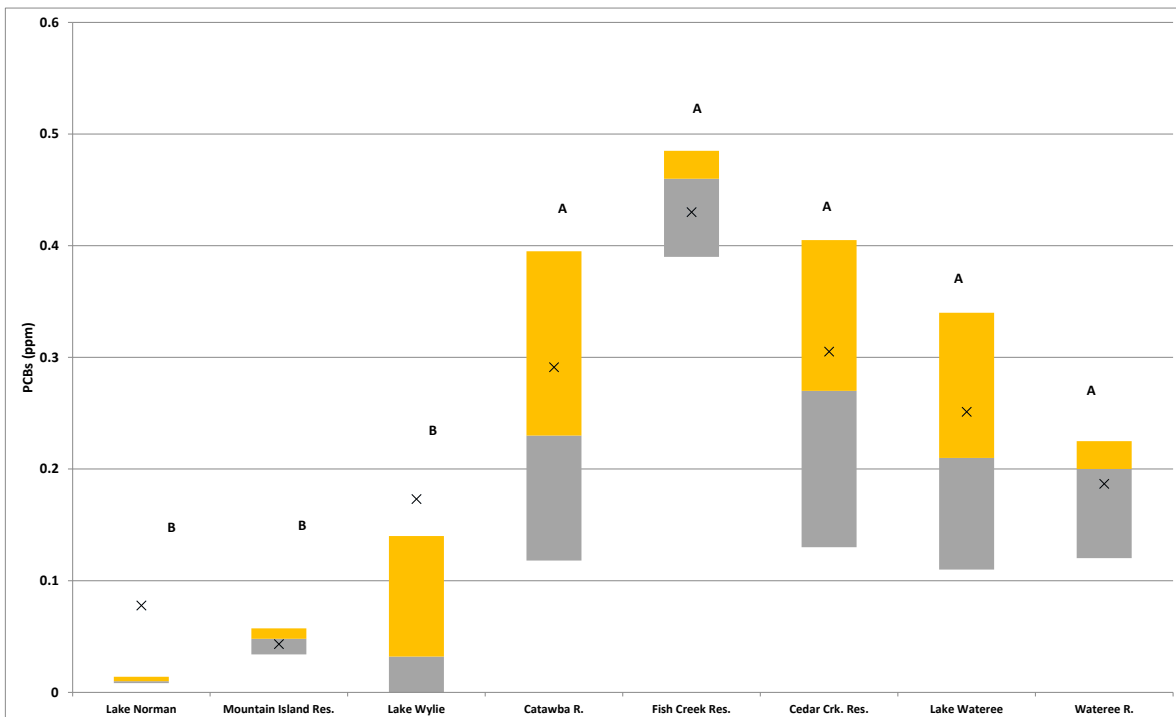


Figure 4. Box plot of PCBs in catfish (blue catfish and channel catfish combined) from water bodies in the Catawba River Watershed showing quartile 1 (bottom of grey columns), median (top of grey columns, bottom of yellow columns), quartile 3 (top of yellow columns), and mean (X). Group means were significantly different (Kruskal-Wallis Test $H=30$, $p < 0.001$). Groups with different letters were significantly different from each other ($p < 0.05$), while groups with the same letter were not significantly different (Dunn's post hoc test).

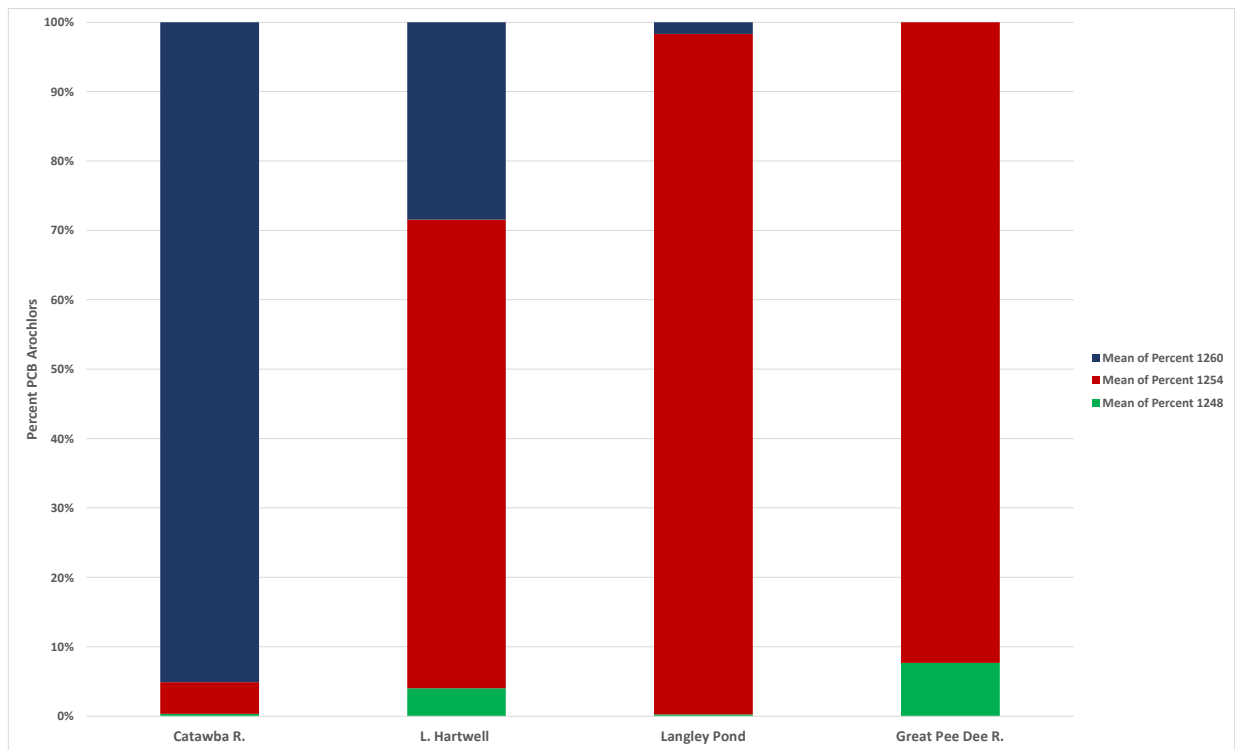


Figure 5. Percent Arochlors in largemouth bass from the Catawba River Basin, the Great Pee Dee River, Lake Hartwell, and Langley Pond in South Carolina.

DISCUSSION

THE USE OF OIL FOR MOSQUITO CONTROL—A BRIEF HISTORY

In the late nineteenth century, a campaign was initiated by the US military and public health officials to stop the spread of malaria, which included an aggressive effort to reduce the population of *Anopheles* mosquitoes (Ross 1900). In the first half of the twentieth century, tremendous volumes of waste oils were applied directly to US waterways, particularly on large reservoirs in the southeast, in an attempt to kill the larvae of the *Anopheles* mosquito (Carter 1913). While Dichlorodiphenyltrichloroethane (DDT), Paris Green, and other pesticides were applied to row crops in and around homes, great quantities were also applied directly to the water’s surface, usually after being mixed with oils of various grades (Johnson 1922).

While malaria in the early part of the twentieth century had been on the decline in the US, there was great concern in the southeast about the many large reservoirs that were being built (Le Prince 1927). The still waters along the shores and in coves provided an ideal habitat for *Anopheles* mosquito larvae. Henry Carter, Senior Surgeon of the US Public Health Service, recognized early in the twentieth century the potential impact on public health of the many hydropower plants that were being planned and provided strong words of warning (Carter 1914). In addition to the concerns of pub-

lic health officials, there were fiscal considerations, as lawsuits were common during this era (Kay 1915; Clark 1931). Williams (1958) reported that in the early twentieth century, “power companies were multiplying impoundments, malaria became epidemic around the new ponds, and resulting lawsuits threatened some companies with bankruptcy.” Malaria was thus a major consideration in planning the construction of hydroelectric plants through the first half of the twentieth century and appears to have consumed much consideration and expense pre- and post-construction (Williams 1958). Duke Energy (2013) reported that their mosquito control program began in 1923 and was the “oldest continuous environmental program of any utility in the US, and one of the first in North America.” Their program continued for 93 years before being terminated in 2016.

EVIDENCE OF TRANSFORMER OIL USED FOR MOSQUITO CONTROL IN THE CAROLINAS

It is not surprising that in May 1970 the participants at a workshop on mosquito control in North Carolina were well represented not only by public health officials and academia but also by utilities, the Tennessee Valley Authority (TVA), and the US Army Corps of Engineers. The proceedings were published in August 1970, which included the questions and answers for the speakers (Howells 1970). To the question of what chemicals hydroelectric plants use for mosquito

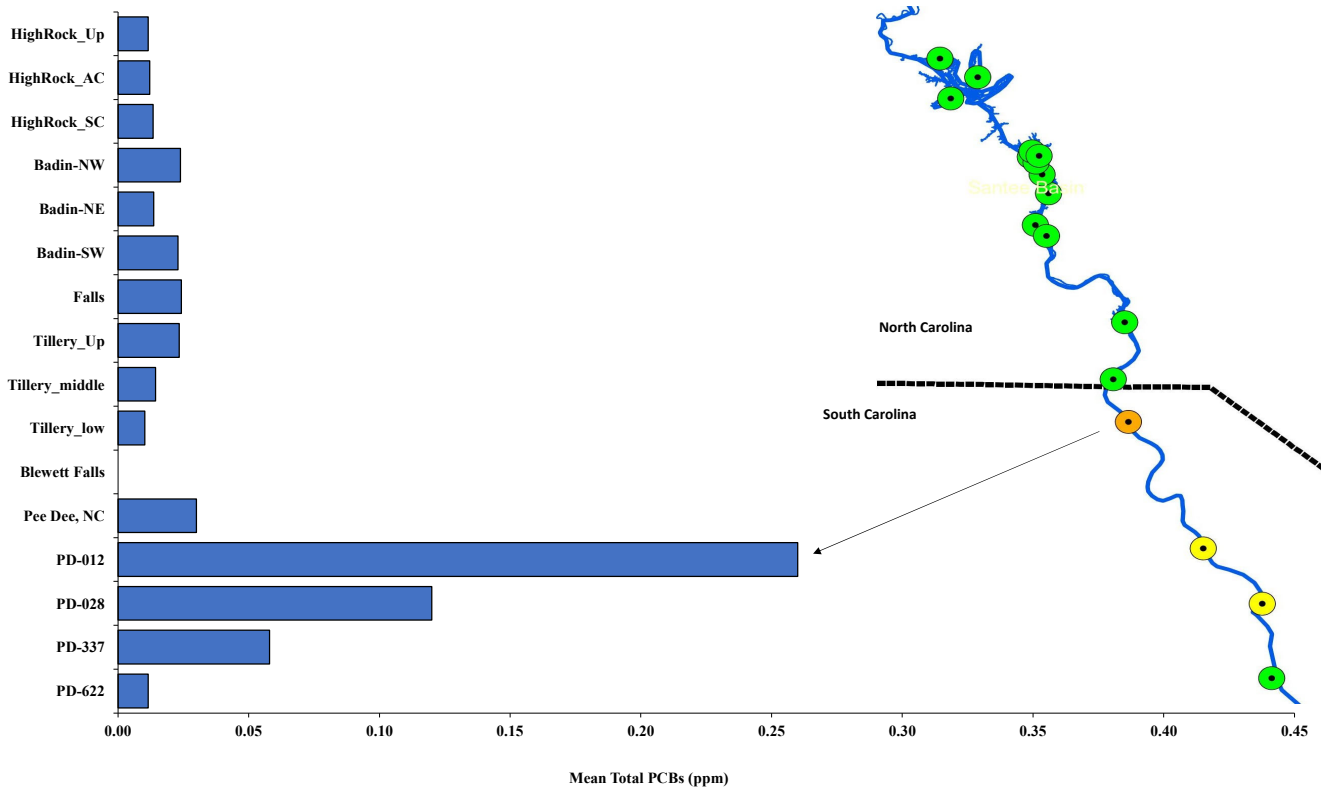


Figure 6. Mean total PCBs (ppm wet weight) in largemouth bass fillets from the Great Pee Dee River Basin. Mean total PCBs for green points <0.05 ppm, yellow points 0.05–0.19 ppm, and orange points 0.20–0.99 ppm.

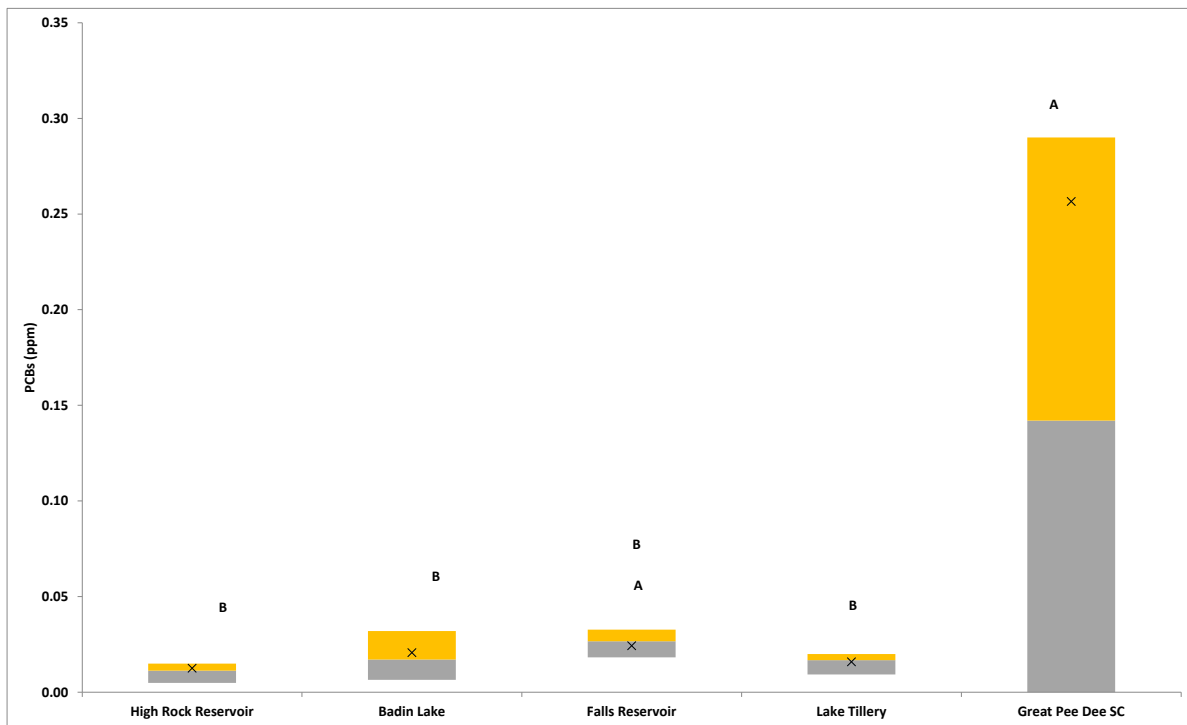


Figure 7. Box plot of PCBs in largemouth bass from waterbodies in the Great Pee Dee River Watershed showing quartile 1 (bottom of grey columns), median (top of grey columns, bottom of yellow columns), quartile 3 (top of yellow columns), and mean (X). Group means were significantly different (ANOVA $F=4.7$, $p < 0.01$). Groups with different letters were significantly different from each other ($p < 0.05$), while groups with the same letter were not significantly different (Tukey-Kramer post hoc test).

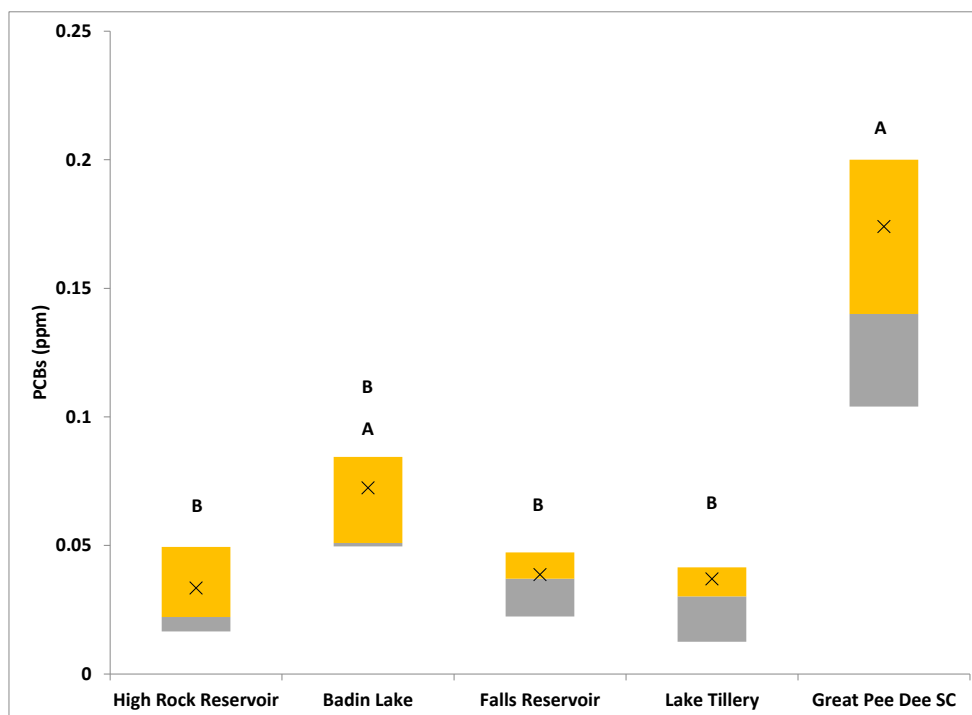


Figure 8. Box plot of PCBs in catfish (blue catfish and channel catfish combined) from water bodies in the Great Pee Dee River Watershed showing quartile 1 (bottom of grey columns), median (top of grey columns, bottom of yellow columns), quartile 3 (top of yellow columns), and mean (X). Group means were significantly different (ANOVA $F=6.3$, $p < 0.001$). Groups with different letters were significantly different from each other ($p < 0.05$), while groups with the same letter were not significantly different (Tukey-Kramer post hoc test).

control, Ashton (1970), with the North Carolina State Board of Health, indicated that a mixture of No. 2 fuel oil and used transformer oil was used by two electric companies. The oil was applied at the rate of 10 to 15 gallons per acre. Swearingen (1970), of Duke Power, reported that they used transformer oil and No. 2 diesel fuel in their mosquito control program. It was estimated that 2,500 miles of shoreline were being treated in North Carolina and South Carolina beginning in April and ending in October, with treatments occurring every 8 days. These are the reservoirs in the Catawba Basin shown in Figures 1 through 4. Harris (1970), with Carolina Power and Light (now Duke Energy) and superintendent of the Blewett Tillery Hydroelectric Project (see Figures 6 through 8) on the Pee Dee/Yadkin River, stated that when transformer oil was available it was used instead of motor oil because it was free. It was suggested that transformer oil had been used for many years, and it was preferred over motor oil because it left a better sheen on the water's surface, which helped the boat operators see where they had sprayed. Motor oil was reported at 20% by volume with the application rate of 150 gallons per day.

The spatial patterns of PCBs in fish shown in Figures 1 through 8 suggest that the past use of transformer oil on these reservoirs contributed, in part, to contemporary con-

tamination. In general, PCBs are absent throughout most of the study area, including large reservoirs operated by other utilities in South Carolina. Where PCBs are present (Lake Hartwell, Langely Pond, and Great Pee Dee River in SC), there is a known point source. The fact that the PCBs found in fish from the Catawba River and Yadkin River reservoirs are Aroclor 1260 (Figure 5; Mort 2017) while those from other sites are mostly Aroclor 1254 further points to these compounds coming from a similar industrial source.

Taken together, these findings strongly suggest that the widespread contamination of PCBs within the Catawba River reservoirs (Figures 2 through 4) and the reservoirs on the Yadkin/Pee Dee (Figures 6 through 8) was caused, at least in part, by the direct application of used transformer oils as part of mosquito control efforts by the reservoir operators. We suggest that the culture of mosquito control and malarial eradication that coevolved with the creation of hydroelectric plants in the early part of the twentieth century likely made the use of waste oil from transformers likely, if not inevitable, at some locations in the Carolinas.

OTHER POTENTIAL SOURCES

Burlington Fibers Plant on Great Pee Dee River, South Carolina

In the fall of 2015, the SCDHEC discovered large quantities of PCBs in soil and sediment around a former Burlington Industrial Fibers plant in Cheraw, South Carolina (SCDHEC 2016). Further investigations found PCBs in the drainage that empties into the Great Pee Dee River near Cheraw, South Carolina (Figure 6). The US EPA, in cooperation with the SCDHEC, soon initiated an intensive investigation of the extent of the contamination. Remediation has occurred and is ongoing, with the site being listed on the National Priorities List (US EPA Superfund) in 2018 (US EPA 2021). The levels and extent of the PCBs in fish tissue of the Great Pee Dee River strongly points to this site as the source of contamination. The predominant Aroclor in the tissue of all fish species in the Great Pee Dee River in South Carolina was Aroclor 1254, but Aroclor 1248 was also present (Figure 5). This pattern was similar to Langley Pond, where the textile industry was also the suspected source. Aroclor 1248 and 1254 were also the primary mixture found in soil samples throughout the area of the former Burlington Fibers plant (SCDHEC 2016). The highest levels of PCBs in fish from the Great Pee Dee River were found at station PD-012, which is immediately downstream from the drainage of the former plant (Figure 6). The decreasing pattern of fish PCBs seen in the Great Pee Dee River moving downriver strongly points to this plant being the source of contamination. This is similar to patterns of PCB in fish from other waterways, with the highest concentrations being near the origin of contamination (e.g., Lake Hartwell in South Carolina; see Gaymon 1992a). The levels of PCBs were much lower in fishes upriver in the Great Pee Dee River in North Carolina, the Yadkin River, and the constructed reservoirs in North Carolina. The homolog pattern from largemouth bass from this basin in North Carolina resembled Aroclor 1260, which was similar to that of the Catawba River fishes (Figure 5). Similar findings were provided in the comprehensive evaluation of fish from the Yadkin Reservoirs conducted by Mort (2017), who showed that the patterns of individual congeners and homologs suggested Aroclor 1260 for most species of fish. It is unlikely that the oiling conducted by the utilities' mosquito control program in the Yadkin reservoirs or the contamination of Badin Lake sediments by the Alcoa plant (see below) contributed to the PCBs present in fish tissue of the Great Pee Dee River in South Carolina.

Alcoa Plant on Badin Lake, North Carolina

The Alcoa plant on Badin Lake also has been shown to have released PCBs into this reservoir and was implicated in the contamination of the fish there (NCDHHS 2012). Remediation, to include capping of lake sediment near the Alcoa plant, was initiated in 2012 as authorized through the

North Carolina's Inactive sites and Hazardous Substance Response Act (NCDEQ 2012). However, High Rock Reservoir, where PCBs in fish have also been found, is upriver from Badin Lake (Figure 1 and Figures 6 through 8), and many of the other Yadkin reservoirs, where PCBs have been found in fish, appeared in the early literature related to malaria eradication and have been managed for mosquitoes for decades (Carter 1915; Gage 1925; Clark 1931). Further, there is strong evidence, including that reported here for the Burlington site, that where point source contamination exists, fish tissue PCBs are highest near the source and progressively lower further from the point of highest contamination (Gaymon 1992a). However, in the three Badin Lake sampling sites, no obvious trends were seen in largemouth bass PCB levels (Figure 6), with the two distant sites having similar levels of PCBs in fish as the site close to the Alcoa plant. The NCDHHS concluded that it was not feasible to link PCBs in fish and people who ate fish from Badin Lake to the Alcoa plant, for reasons that were enumerated by NCDHHS (2012). We support this view and suggest that application of transformer oils for mosquito control may have contributed to the contamination seen in Badin Lake.

Past Industrial Pollution

The discovery of large quantities of PCBs at the former Burlington Fibers site on the Great Pee Dee River in 2015 serves as a reminder that past industrial releases may remain undiscovered. A large portion of the city of Charlotte is in the Catawba River drainage, with much of the urban land area draining into the Catawba River through Sugar Creek (Figure 1). Data from the 1970s (Aldridge 1978) to date shows that levels of PCBs in fish tissue are consistently higher in fish below the confluence of Sugar Creek and the Catawba River in South Carolina (Catawba River, Fishing Creek Reservoir, Cedar Creek Reservoir, Lake Wateree, and Wateree River) than above in North Carolina (Lake Wylie, Mountain Island Reservoir, and Lake Norman) (Figures 1 through 4). The detection of PCBs in fish tissue of the Catawba River proper near the Catawba Indian Nation (US EPA 2016), where mosquito oiling likely did not occur, further points to additional sources (Figure 1). However, most of these reservoirs on the Catawba River were completed before 1930 while Lake Norman is a relatively newer reservoir (formed in 1963) (Table 1). There would thus be a shorter history of mosquito control on Lake Norman than on other Catawba Reservoirs, which could explain the relatively lower levels of PCBs in that reservoir. However, this does not explain the relatively lower levels in Mountain Island Reservoir (constructed in 1924), suggesting that other sources of PCBs may have contributed to the relatively higher levels of contamination in the downriver reservoirs of South Carolina.

Regardless of potential other sources, the widespread contamination in the reservoirs managed by Duke Power

and Carolina Power and Light (both now Duke Energy), and Alcoa Corporation (now Cube Energy, LLC), along with the acknowledged use of transformer oil in the operations mosquito control programs, strongly suggests that some of the contamination is from the direct application for mosquito control.

CONCLUSION

The global ramifications of these findings are numerous. It is unknown whether PCB waste oils were used by other mosquito control programs. The only documentation we found was from the proceedings of the Mosquito Control Workshop in North Carolina (Howells 1970). However, even here this could have escaped scrutiny if the post-presentation questions and answers had not been captured in the proceedings. Outside of this workshop and the published proceedings, it is also unclear how widely the idea of using spent transformer oils for mosquito control was shared with other regional operators. While the Tennessee Valley Authority (TVA) used oiling on their many reservoirs, water elevation management became an increasingly more important part of its mosquito control program than oiling (Gartrell and Ludvick 1954; Breeland et al. 1961).

In reservoirs where PCBs have been detected, but an obvious source has not been identified, a reevaluation of data and literature would seem appropriate. Many of these hydroelectric projects occur in the southeastern US, but oiling has been a staple for mosquito control throughout the world, even in regions where malaria does not exist. Early research found that PCBs were toxic to the larvae of *Anopheles* mosquitoes (Deonier et al. 1947), but it appears that the primary application was to extend the effective life of other pesticides such as Lindane (Duda 1957). A prerequisite to suppose an association of contemporary PCB contamination with legacy mosquito control would require the same components that were seen in our study, such as a mature and well-funded mosquito control programs, presence of PCBs in the fish of the treated reservoirs but absent in others, and a ready supply of PCB oils that were expendable, likely in combination with other waste oils.

We believe consideration should also be given to remote locations where PCBs have been discovered. There is a large body of literature on this topic, with much of it focused on atmospheric transport and deposition of PCBs traveling great distances from their original source (Bright et al. 1995). For example, some of these projects have occurred in the arctic, with PCBs being discovered far from any known source and in remote areas in this region (Freidman and Selin 2016). Mosquito control in the arctic and subarctic, as elsewhere, is well documented in the historic literature, with the same means and methods employed for eradication (Twinn 1950). For example, using aircraft, 2,777 gallons of a diesel

oil mixed with Dichlorodiphenyltrichloroethane DDT was used to cover 3,500 acres of test plots near Churchill, Manitoba, Canada, in 1947 (Goldsmith et al. 1949). In a thorough review on control of biting flies in Northern Canada, Twinn (1950) reported on experimental control measures being carried out at Fort St. John and Fort Nelson, British Columbia; Watson Lake and Whitehorse, Yukon Territory; Goose Bay, Labrador; Rockcliff, Ontario; and Churchill, Manitoba. As was common during this period, DDT mixed with oil sprayed from aircraft was the primary form of treatment in these experiments, with up to 43 square miles being treated in some studies. The mixtures of these treatments were well documented by Twinn (1950) and appeared to consist solely of fuel oil, kerosene, and methylated naphthalenes as emulsifiers for DDT. However, Nordin et al. (1993) suggested that some petroleum oils in the Yukon Territories could have been contaminated with PCBs and that these could have been used in the region's mosquito control programs. It is unclear if PCB oils, when available, were used intentionally in subarctic mosquito control programs, but our findings suggest that this should be considered in future investigations.

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Widespread Contamination of Polychlorinated Biphenyls in South Carolina and North Carolina

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Health Communication Blindspot: A Case Study of Harmful Algal Blooms in the South Atlantic States

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Abstract. A Harmful Algal Bloom (HAB) is a complex natural event that occurs when algae reach a critical biomass and create one or more toxins harmful to biological life or the environment. By definition, HABs create both ecological and public health challenges. Because governments are the entities most often tasked with the responsibility for shared resources, this case study represents a snapshot of current governmental messaging about HABs in the South Atlantic states. The objective of this online content analysis is to determine the readability of both state and federal government online communications regarding HABs using the Simple Measures of Gobbledygook (SMOG) test. Sources for this study were obtained using a targeted search of both South Atlantic state websites and federal agencies concerned with HABs and their effects on human health. In total, 90 webpages were identified from state (n=38) and federal agencies (n=42), as well as nongovernmental organizations (n=10). The average SMOG score of all 90 sources is an 11th grade reading level (10.7). This content analysis reflects the complexity of scientific communication. However, as evaluation and improvement are the final steps in any public health programming, evaluation needs to be undertaken in all environmental health communications in order to properly inform the public about known toxicological and environmental health risks.

INTRODUCTION

The purpose of this study was to determine the readability of online content related to Harmful Algal Blooms (HABs) and to contribute to the knowledge of public-facing environmental health communications. Not only are HABs common to the state of South Carolina, but they are also increasing in frequency and intensity (Gobler 2020). Health communicators and water resource managers will be able to use the principles in this analysis to better relay information relevant to the protection of public health and the health of the environment. This content analysis allows those charged with informing the public to better understand the current landscape of publicly available HAB information and potential areas of improvement.

BACKGROUND AND RELATED WORK

A Harmful Algal Bloom (HAB) is a complex natural event that occurs when algae reach a critical biomass and create one or more toxins harmful to biological life or the environment (Maso and Garcés 2006). By definition, HABs create both ecological and public health challenges. To best protect both public health and the ecosystem, communication principles

and practices are crucial to provide water users with accurate information regarding HABs. Because governments are the entities most often responsible for shared resources like water, this case study represents a snapshot of current governmental messaging about HABs in the South Atlantic states. These states have a long history of HAB events in both fresh and marine water environments (Lewitus and Holland 2003; Lopez et al. 2008; Greenfield et al. 2017). Intense urbanization, nutrient loading, increasing water temperatures, and ocean acidification have all contributed to increased recorded HAB events in recent years (Wells et al. 2020; Paerl and Paul 2012). HAB increases worldwide require a public health response reciprocal in magnitude (Brooks et al. 2016). As this region continues to face booming population growth, the issue of HABs will continue to play a role in the development and exploitation of coastal communities.

The Plain Writing Act of 2010 mandates plain language design in federal communications “to enhance citizen access to Government information and services by establishing that Government documents issued to the public must be written clearly.” Following suit, many states have adopted similar policies to ensure that citizens have access to information that is understandable and digestible to the nonexpert public. The

A Case Study of Harmful Algal Blooms in the South Atlantic States

strategies employed by health communicators to create communications that meet these simple criteria are collectively referred to as plain language design (PLAIN 2020). However, as will be shown, not all public-facing scientific communication is written in a manner that is easily understood by the populations who most need the information.

Beyond the importance of transparency in business dealings in the name of public trust, government agencies are under legal mandate to take measures to create communications that are understandable to everyday Americans. As mentioned, the Plain Writing Act of 2010 outlines simple practices to be used by federal agencies to better communicate with the country. By July 13, 2011, agencies were required to (1) designate an official for “plain writing,” (2) educate staff on plain writing principles, and (3) create a quality assurance process for compliance to the act, among other requirements. It should be noted that the American Bar Association, of which a plurality of policy makers at all levels of government are members, also urges its members to use plain language in all communications (PLAIN 2020). If the public cannot understand the information presented to them from their own government, it is illogical to assume that the public will be capable of making an informed risk characterization.

When the public is receiving risk information from various outlets, it becomes difficult to accurately qualify public risk assessment capacity. Households within communities may also differ in their preferred communication channels. With the rise of social media, it is increasingly important that succinct and accurate risk information is widely available (Strekalova 2017). In localized emergency settings, such as HABs, word of mouth has been cited as the most common and effective communication strategy (Wolkin et al. 2019). Given the rapid pace of technological advancement and the social isolation of a digital age, a hybrid communication strategy that implements multiple communication channels will become increasingly important, as relying upon word-of-mouth communication may be insufficient. Thus, HAB-specific information consistent with current health communication science will provide a tool for mass media, social media, or in-person communicators necessary to properly communicate environmental risks to the public (Stellefson et al. 2020).

The scientific community often grapples with the difficulties of disseminating evidence-based messaging to a lay public audience. One emerging field in environmental health sciences is environmental health literacy (EHL). As a discipline, EHL rests between environmental scientists concerned with environmental exposures, and their effects on human health, and health communicators who inform the public on proper risk characterization and classification so as to mitigate or eliminate the risk altogether. EHL has far-reaching implications as the backbone to many community-based

participatory research (CBPR) projects. Due to the nature of environmental sampling, many scientists are turning to citizen-science in order to gain additional data for analysis (Sullivan et al. 2018). Citizen-led data collection efforts allow scientists to gather wide swaths of data by increasing the volume of participation. EHL helps to bridge the gap between scientists and citizens and allows researchers to better disclose their findings to the general public.

Finn and O’Fallon (2017) describe the history of EHL as a blend of health communication and deeper understanding of the corollaries between exposure and human health impacts. The researchers connect iconography with health communications such as a skull and crossbones to symbolize potential danger, or the ever-growing symbols currently used by militaries around the world to denote specific dangers like nuclear radiation or toxic chemicals (Finn and O’Fallon 2017). One successful example of EHL is the implementation of environmental sensitivity index mapping for use by emergency responders to an oil spill. While the hazards of oil spills in aquatic areas were well known, emergency responders often failed to understand just how to protect specific habitats from the devastation of a spill. Iconographers created simple designations so as to direct responders to environmentally sensitive areas and the best practices for protecting those areas. (Jensen et al. 1998).

Especially in terms of water-related issues, the technique of online content analysis around environmental hazards is not without precedent. A 2016 study of online resources related to the risks of seafood consumption was published by researchers from the University of South Carolina (Henderson et al. 2016). While the risks of HAB exposure do not have a compensatory benefit as is seen in seafood consumption, the overlapping audiences provided a pattern for this study to follow in discussing issues relevant to both online health communicators and environmental resource managers. However, no known study relates American public perception to HAB risk communication, and as such, health communication examples from other public health risks will play a significant role in the establishment of environmental health communication norms for HABs and similar events.

PROJECT OBJECTIVES/GOAL

The goal of this study was to evaluate the current readability of HAB webpages maintained by government entities inclusive of public-facing resources.

MATERIALS AND METHOD

Sources for this online content analysis were obtained using a targeted search of both South Atlantic state websites and federal agencies concerned with HABs and their effects on human health. These agencies include both health

and environmental departments, which in some cases are combined but in many are separate government entities. The South Atlantic states, inclusive of North Carolina, South Carolina, Georgia, and Florida, were selected as states of interest due to their increasing frequency of HABs as well as their geographic similarities and proximity. State website searches included those of both health department sites and environmental resource management sites such as the North Carolina Department of Environmental Quality (NCDEQ). Searches were limited to “.gov” web addresses due to significant increases in credibility scores when compared to “.com” sites among a nonexpert audience (Treise et al. 2003). Websites were evaluated as a whole but were specific to each individual web address or URL. The use of the terms *webpage* and *website* is not interchangeable, but for the purposes of this study, these terms are most often used to define a specific web address. The logic behind this methodological approach is based on the idea that information seekers are unlikely to follow multiple links to find the information they are looking for (Pang et al. 2015).

To establish a readability score, the text from each webpage was evaluated using the Simple Measure of Gobbledygook (SMOG) test, a validated tool for the assessment of readability (Friedman and Hoffman-Goetz 2006). The SMOG test has been the standard in evaluating text complexity since its creation by clinical psychologist Harry McLaughlin (Fitzsimmons et al. 2010), and although originally used in the field of education, SMOG has become the primary measure used to evaluate health-related information. The SMOG test is a measure of readability that assesses sentence structure by counting every word of three or more syllables (Grabbe et al. 2018). The basic rationale behind this test comes from speech and cognitive developmental processes that indicate that words of two or fewer syllables tend to be more frequently used and easily understood by a general audience. As words become more technical, and as sentences include more field-specific jargon, the SMOG score in a sample of text will increase. For the SMOG test to be valid, the text to be evaluated needs to contain at least 10 sentences; thus, some of the excluded sites simply did not have enough content for inclusion using this method. Sentences were scored by an online readability calculator (<http://www.readability-formulas.com/free-readability-formula-tests.php>) to obtain a score that correlates to a US school grade level. This grade level estimate is often used in many fields—and is prevalent in health care—to provide a normalized metric to text on diverse health topics (Kim and Xie 2017). Given the scientific density and complex vocabulary of both health care and environmental science, the SMOG test with its accompanying grade level scoring system provides a logical evaluation tool for the field of environmental health science.

As discussed previously, management of water resources falls under the purview of various state and federal agencies,

depending on the location of waters and the legal context of a given situation. As such, federal agencies that were likely to have HAB information that would affect residents of the South Atlantic states were included in this analysis. Websites were grouped into two broad categories as either related to (1) users of water resources like stand-alone health departments similar to the Florida Department of Health or the CDC, or (2) managers of water resources like the South Carolina Department of Health and Environmental Control (SCDHEC) or the US EPA. This distinction was made based on the known gaps in scientific literacy among the two target communities (Guidotti 2013). Because this study was designed to assign median scores to multiple webpages from permanent agencies, blog posts such as “news” updates that are frequently posted on sites were excluded from governmental agencies.

Since governments are not the only organizations with an interest in the management of water resources, nongovernmental organizations (NGOs) were included as a referent group. However, these organizations do not always maintain websites. In an effort to provide statistical power, “news” posts were selected from NGOs to have a large enough sample to draw intergroup comparisons relating NGOs to state and federal sources. The NGOs selected for this study were waterkeeper organizations such as the Congaree Riverkeeper and the Charleston Waterkeeper. The Riverkeeper and Waterkeeper alliance is a nonprofit organization dedicated to protecting rivers at a local level. Riverkeepers from each state in the South Atlantic region were identified. The NGO class was primarily included for comparison of descriptive analytics to state and federal sources. These organizations are a grassroots effort to protect water resources and are typically composed of a limited staff of one or two individuals and multiple volunteers. Beyond geographic exclusion to the South Atlantic states for NGO, state agencies, and federal agencies of the United States, no other exclusion criteria were followed outside the “.gov” stipulation for inclusion. Sources were gathered in December 2019 and again in February 2020. Because most people seeking health information today use online resources (Morahan-Martin 2004), an internet search was conducted to establish health communication practices using the specific terms. A source qualified as an HAB communication if it contained the words “toxic algal bloom,” “harmful algal bloom,” or “HAB.”

Mobilizing information in health communication is information that leads to further action on the part of the receiver. The theoretical backing of mobilizing information is the Health Belief Model (Rosenstock 1974) and has been applied to health education as a means of evaluating the quality of online health information (Friedman et al. 2008). Mobilizing information relies on preexisting attitudes, such as information seeking, which is manifested by visitation of a site regarding HABs. These cues to action are an indica-

A Case Study of Harmful Algal Blooms in the South Atlantic States

tor of health behavior and can include contact information, checklists, or links to further information. Although not an explicit construct of the Health Belief Model, cues to action are also used in environmental science, as is seen in the various advocacy groups around the globe. The aspects related to mobilizing information are documented as an additional layer of analysis.

Health numeracy, defined as the ability of a person to understand quantitative health information, is also a necessary component for evaluation. As a means of conveying risk information, numeric data has been shown to complicate comprehension for a public audience (Peters 2008). Sites containing numeric information such as charts and tables was recorded and reported in the final analysis as comprehension aids. Further, carefully created maps have been shown to enhance community perception on environmental risk (Severtson and Vatovec 2012). The inclusion of a map or a link to a map was recorded as a measure of comprehension aids provided on each site. Other measures identified in the results section are defined there, but the broad terms here are supplied for context. Relevant measures and their definitions may also be found in health communication literature.

A codebook was modified from the codebook used in a previous study by Henderson et al. (2016), described above, for analysis of the targeted search. SMOG readability scores were analyzed, and individual agencies were given a composite score of the median readability grade level based on the sites the agencies produced and maintained. The complete codebook can be found in Appendix B. Sources for necessary codebook amendments and adaptations for this study are noted at the end of the codebook itself for reference.

The data analysis for this study was generated using SAS University Edition software for Windows (SAS). Statistical tests included preliminary Chi-square or Fisher's exact tests as appropriate, followed by a simple linear regression model with the SMOG score acting as the outcome variable.

RESULTS

Table 1 enumerates all sources by their class affiliation: state, federal, and NGO (Riverkeepers). In total, 90 sources were identified, which consisted of 38 state sources, 42 federal sources, and 10 NGO webpages. Table 1 lists state and federal sites. State sites are grouped together by state, and federal agency sites are identified by the number of sources identified that are maintained by each individual organization. A complete list of all webpages identified can be found in Appendix A.

The mean SMOG score of all 90 sources was 10.7, equivalent to an 11th grade reading level in the United States education system. State and federal webpage comparisons showed a statistically significant intraclass relationship ($p=0.0217$) using the Chi-squared test: χ^2 (df 2, $n=90$) = 7.6601. Fish-

er's exact test of independence was also used due to a relatively low expected value for sources with a SMOG score less than the cutoff point of 9, and it signaled significance ($p=0.0025$). States were more likely to have a reading level under 9th grade than federal pages by a ratio of 12:5. NGOs undertake different missions and indeed have different stakeholders than governments. As such, NGO sources were not compared for independence to state and federal sources.

Of all webpages, 47% ($n=42$) listed a date when content was modified. Over half of the webpages, 59% ($n=53$), were written in paragraph form, and 60% ($n=32$) of paragraph pages utilized chunking. Overall, 3% ($n=3$) of sites required clicking next to see all content, including two Florida webpages and one NOAA page. Some sort of glossary or term definition was included in 29% ($n=26$) of webpages, with 2 of the 42 federal sources (4.76%) meeting these criteria. Although 18% ($n=16$) had an electronic mailing list or newsletter, these were almost exclusively observed among NGOs (9 out of 10 NGO sources analyzed representing over half of all mailing lists identified). Out of all sources, 4% ($n=4$) were written in the second person, with the F-pattern of web design used on 69% ($n=62$) of all pages with 42% ($n=38$) using typographic cues.

Webpage focus was determined by a review of the content with a 75% threshold that best aligned with 1 of 3 classifications with a relatively even distribution: Biochemistry (31%), Ecological (40%), and Public Health (29%). Importantly, 57% ($n=51$) included a warning about human exposure, and 37% ($n=33$) included an animal-specific warning about exposure ($n=33$). About a third of sites, 37% ($n=33$), described specific bodies of water, including all 10 NGO pages. Almost half, 44% ($n=40$), had a call to action, but no webpages contained a summary or takeaway section.

Specific toxins are important in medical diagnostics and water management. Of the sites, 19% ($n=17$) mentioned specific toxins with the common freshwater toxins of Microcystin (13), Cylindrospermopsin (9), Anatoxins (7), and Saxitoxins (7)—the last of which can be produced in both fresh and saltwater conditions—being enumerated most frequently. Further, 8% ($n=7$) mention specific diseases and syndromes resulting from human HAB exposure. With the science showing that the naked eye cannot reliably identify an HAB, 39% ($n=35$) list at least one way to identify an HAB without laboratory techniques, and 30% ($n=27$) list activities to avoid when an HAB is suspected.

Unprompted pop-ups were only observed on federal sites; these asked consumers if they were willing to take a survey to improve the site. Over half of the sources, 58% ($n=52$), contained links to outside sources and information, with an average of 5 sources per page (4.70 links). The 2 sites with the maximum number of links provided were by the NGO Albe-marle Resource Conservation and Development Council (26) and the CDC (17). Only 6% ($n=5$) contained the logos

Table 1. Agencies Represented

Class	State/Agency	Abbreviation	Sources
State	North Carolina	NC	12
	Florida	FL	14
	Georgia	GA	4
	South Carolina	SC	8
	State Total		38
Federal	Centers for Disease Control and Prevention	CDC	12
	Environmental Protection Agency	EPA	9
	Fish & Wildlife Service	FWS	1
	National Park Service	NPS	1
	National Institute of Environmental Health Sciences	NIEHS	1
	National Oceanic and Atmospheric Administration	NOAA	6
	US Department of Agriculture	USDA	7
	US Geological Survey	USGS	5
	Federal Total		42
State & Federal Total		80	
NGO	Riverkeepers	RVKP	10
TOTAL			90

of other organizations, indicative of collaborative activities. All 5 pages with other organizational logos were academic presentations hosted on government sites. Because multiple federal agencies were represented by only 1 webpage, most analyses were performed using statistics grouped by class.

Figures 1 and 2 show median SMOG scores among state and federal agencies, respectively. Ultimately, 10% error bars were used for two main reasons: (1) using only one coder, or website reviewer, has a greater potential for researcher bias to influence results, and (2) because the SMOG formula involves counting specific words, the variation of word counts on each page is not completely comparable across every source. These two figures illustrate the intraclass variation in SMOG scores. The maximum median SMOG score is the US EPA score of 14.68 represented by 9 different webpages. The minimum agency SMOG score of 7.0 represented by a single webpage was another federal agency, the US Fish and Wildlife Service (FWS). Taking an aggregated average of median SMOG scores by state, federal, and NGO classes yields 10.41, 10.97, and 11.32, respectively. State and federal classes are represented by 38 and 42 sources, respectively, while the median NGO score was obtained from 10 sources.

A simple linear regression model fits SMOG score data in Figure 3. The y-axis in this linear regression shows SMOG scores from 5 to 20 to more clearly display the positive slope of the linear regression between the state and federal sources. Each state observation is indicated along the left side of

the graph by red circles, while each federal observation is indicated along the right side by blue squares. Dotted lines represent 95% prediction limits. This model contains 80 observations with 2 parameters (state and federal). Despite the relatively large mean square error (MSE) of this model of 7.469, with an R² value of 0.0565 there is almost no statistically significant correlation in the relationship between state and federal agency distinction and associated webpage SMOG scores, using logistic regression. Both of these results could be partially explained by the small sample size. As more webpages are added around this issue, the model could improve.

Each webpage's focus was coded with 75% threshold criteria with 3 classifications, with an ecological focus representing the plurality in the identified sources: Biochemistry 31% (n=28), Ecological 40% (n=36), and Public Health 29% (n=26). All 90 observed webpages are indicated in the radar chart in Figure 4, which is designed to show relative frequencies. Each circle, or band, from the center represents an additional 10% frequency. Given the distribution, Biochemistry and Public Health foci fall along the same band, and the Ecological focus lies on the outermost band, indicating a 40% frequency.

A Case Study of Harmful Algal Blooms in the South Atlantic States

SMOG Scores. *Error bars represent a standard 10% errors

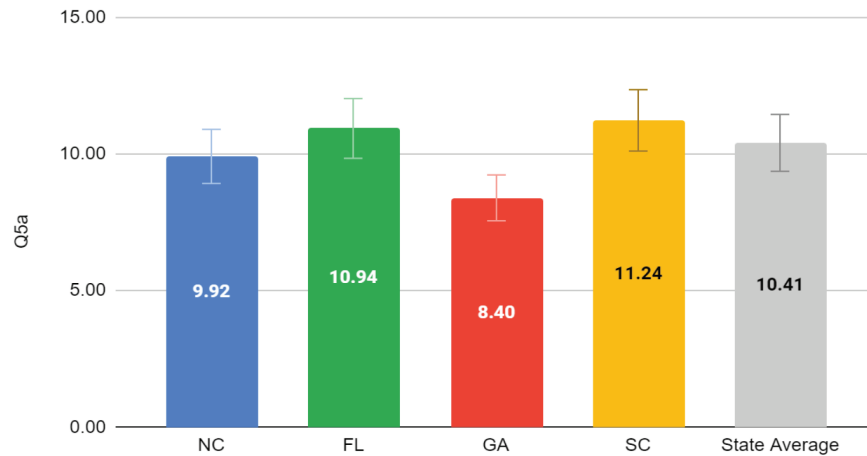


Figure 1. State SMOG scores.

SMOG Scores. *Error bars represent a standard 10% errors

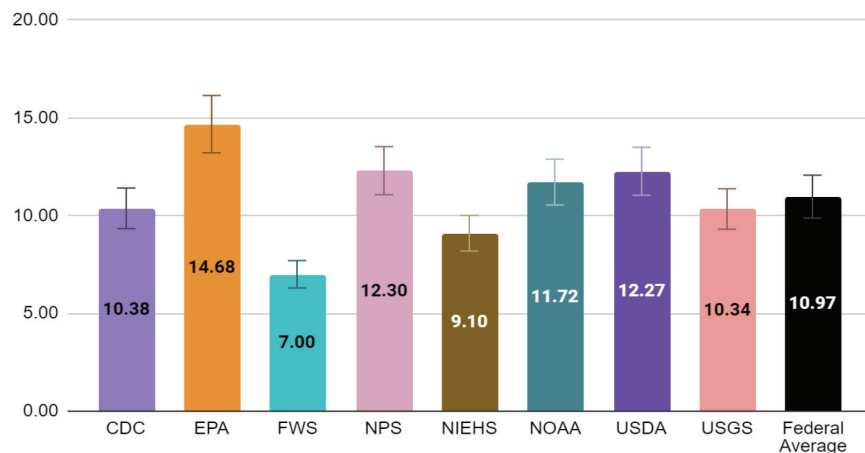


Figure 2. Federal SMOG scores.

DISCUSSION

This analysis indicates the potential for the development of prescriptive measures to increase public awareness and compliance with public health recommendations. As Rimer and Kreuter (2006) suggest, tailored health communication is the best route for HAB communications moving forward. Luckily for health communicators, audiences are already geographically segmented and can thus receive communications better tailored to the water quality in their location. Although educational attainment is closely tied to health literacy (Jones et al. 2012), plain language design continues to influence risk perception across demographics and geographies (Ferrer and Klein 2015). The best strategies in health communication have long been studied in health

care settings, and health communicators apply the same logic to the ecological domain (Fitzpatrick-Lewis et al. 2010). As a general guide as noted above, public-facing information should score no higher than 9.0, if not lower. The combined score of 10.7 indicates a grade-level reading score of 11th grade and shows clear room for improvement.

SMOG scores were the primary measure of this content analysis. There was an observed statistical difference between states and federal sources. The NGO class was excluded from regression analysis due to low expected values given the comparatively lower number of identified sources. In SMOG analysis, the 9th grade cutoff has long been used as the gold standard for communications to simultaneously maintain necessary topic-specific complexity and simplicity that matches the literacy level of the general public (Walsh and

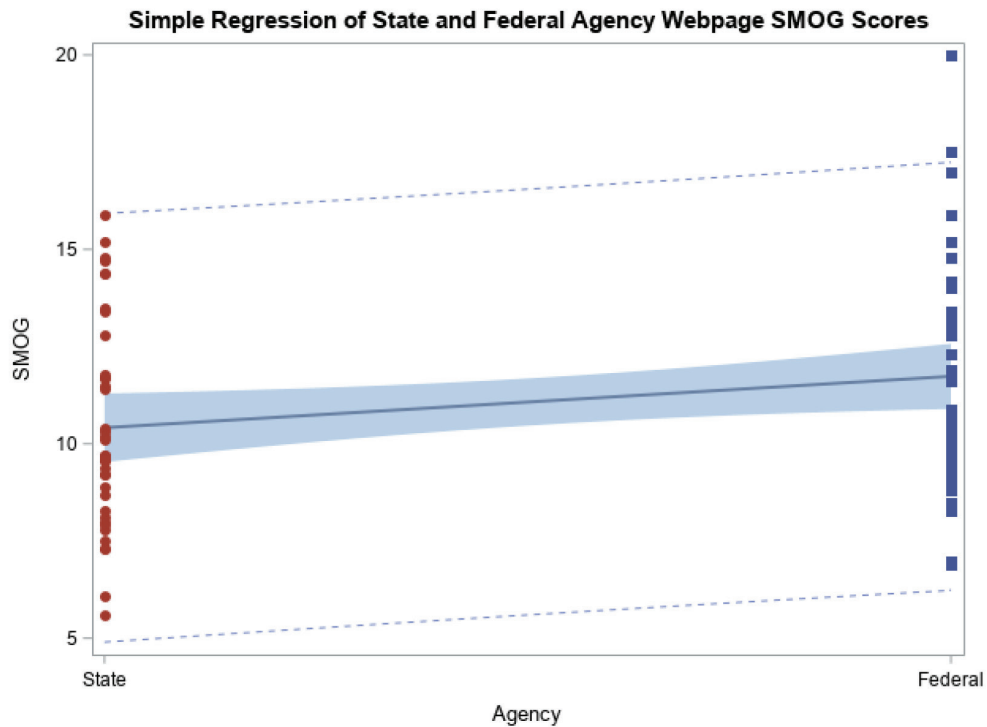


Figure 3. SMOG score simple regression.

Page Focus

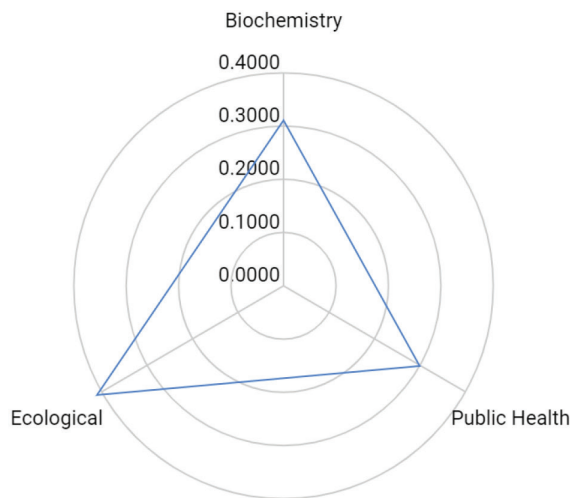


Figure 4. Page-specific focus.

Volsko 2008). This has been a mass communication standard despite the fact that the nationwide high school graduation rate rose to 94% in 2020 from 72% in 1980 (NCES 2020). The median SMOG score of all sources was 10.7, equating to an 11th grade reading level. An examination of the arbitrary 9th grade cutoff should be considered with all other results presented here. As shown in Figure 3, simple linear regression did not yield a strong correlation between increased

SMOG scores based on state or federal classification, despite the noted statistical difference. This was likely due to the wide spread of the data to include outliers, such as the low SMOG scores in Georgia or the relatively high SMOG scores in US EPA communications.

The results of this analysis are troubling on one hand, but on the other, they show organic means of simple and rapid improvements. Perhaps the simplest solution for all

A Case Study of Harmful Algal Blooms in the South Atlantic States

sites to increase their readability is to include summary or takeaway sections. These sections are particularly helpful within an environmental hazard context. Consumers of the information found on these sites are often looking for quick facts to help with their risk characterization and determination. Readability can also be improved with shorter paragraphs, known as chunking, and the use of bullet points. A frequently asked questions (FAQ) page would also be helpful for all sites. These solutions help online information seekers find answers to their questions in an efficient manner without requiring them to scour more information than is applicable to their unique needs. Figure 4 shows how government communicators tend to triangulate information about HABs around the biochemistry or physical processes of HABs and their ecological and public health determinants and consequences. The sites identified are relatively balanced between these three topics, which can generally help information seekers find what they are looking for despite their varied needs and backgrounds.

As noted previously, HAB intensity and causative organisms vary in freshwater and marine water. Given the difference in coastline length between Florida's long coast and Georgia's relatively short coast, Georgia faces a greater ratio of freshwater HABs compared to Florida's propensity for marine HABs. Federal pages also consider inland states like Kansas that have no coastal waters alongside Alaskan waters with 33,904 mi (54,563 km) of coast as measured by the NOAA method (NOAA 1975). Describing salinity is particularly pertinent to this study because HABs are not just a coastal phenomenon or problem. Sites identified by this study tended to describe salt and brackish water HABs, but freshwater HABs were not excluded from consideration or discussion. Much of what we know about which algal species thrive in certain environments is based on water salinity. As each of these 4 states, and indeed all 50 states, face a different HAB landscape and environment, it is too simplistic to prescribe any specific toxins or diseases that should be included on all webpages. However, common symptoms of all ingested HAB toxins are similar to food poisoning, and inhaled HAB exposure typically presents with airway aggravation. Contact dermatitis, or swimmer's rash, is the most common result of dermal HAB toxin exposure. All of these symptoms could responsibly be included on HAB websites. Proper audience segmentation for health care practitioners, researchers, and the general public will allow these sources to maintain various levels of complexity (Paige et al. 2017).

Audience segmentation can be improved with a wide variety of web design tools. All pages had at least one measure of content and subsequent web design that could be improved. Used in this content analysis as a proxy measure, organizational logos can be indicative of interorganizational collaboration. Links were often provided to external organizations and agencies, but if the scientific collaboration ends

there, the public suffers from incomplete scientific experimentation. Academic papers are peer-reviewed, but one recommendation for government agencies would be to institute agency-wide checklists for an interagency review of all new scientific information. This would likely result in a minor delay in disseminating new information, but this method would allow agencies and organizations to avoid providing the public with conflicting information. Few aspects of public communication can ruin institutional reputation and public perception as much as conflicting messaging can.

The scientific method relies on falsifying null hypotheses rather than attempting to prove alternative hypotheses. Causation is not correlation primarily because it is difficult to control all external factors in an experiment, thus creating a dilemma for health communicators. Confounding factors make disseminating and generalizing results extremely difficult. The dietary recommendation for one study population could have the exact opposite effects for another population (e.g., a prescriptive Mediterranean diet for someone with severe seafood allergies). Health communicators must understand the implications of the science while maintaining public perception of transparency.

Even when mounting evidence shows adverse health effects from risky behavior or new exposure, there are moral implications to human experimentation. HABs have produced health outcomes ranging from mild rashes to death and have been observed in multiple species. As we await the advancement of science to improve the detection of thresholds of safe HAB toxin exposure, as well as technological advancements that allow water managers to quickly and accurately assess various water sources, the precautionary principle (Kriebel et al. 2001) should be applied to HABs. With declining public trust in governments and low scientific literacy among Americans, environmental health communicators have a challenging task to properly characterize the risk of HABs.

This study does contain many of the same limitations common to all content analyses. While every effort was made to sample as many sources as possible within the representative agencies, it is possible that certain pages were not analyzed given the methodological approach that is reliant on search engine algorithms. The single coder dilemma was also a limitation, as implicit bias was introduced because only one researcher participated in data collection. Another possible limitation was the study period, as some sites were updated during the study. Despite these limitations, this content analysis contains valuable information that can be applied immediately to environmental health sciences in the form of online risk communications.

CONCLUSION

The findings of this study provide at least 2 specific items that can and should be implemented by governments. First, readability standards should be created and standardized prior to any webpages being released on the internet. Making readability a gatekeeper for information to be communicated to the public provides greater operational efficiency as there is less confusion between government communicators and their audience. Readability standards also create a simple way for citizens to keep governments accountable for informing the public regarding shared resources under the respective government's care. Second, regular readability evaluation schedules should be created to evaluate social media and other "news" items or blog posts. These communications tend to be rapid-release and thus may not necessarily be subject to review by an assigned communications officer. Thus, a retrospective analysis can be performed to better facilitate future direct communications by subject matter experts. This will help subject matter experts communicate more clearly to their target population as well as improve public awareness of specific issues as misconceptions are identified and addressed. Given the diverse ways the public interacts with water resources and affects water quality, these simple actions by governments will at the very least create a more responsible framework for communicating risks about HABs.

Although some agencies were shown to have more readable content than others in this study, these results represent a single moment in time. As web content is refined, these pages have the potential to improve. Communication researchers will continue to study information interpretation and processing, resulting in different criteria for measuring the effectiveness of health communications over time. Public input should also be considered in evaluating readability to determine comprehension and the efficacy of environmental health communications. Perhaps the most salient example of future directions would be the creation of a quick reference for what the public needs for an HAB webpage. This tool could be developed rather quickly but would need to involve all stakeholders described in the study at hand. Future researchers should consider ways to evaluate public trust as a means of measuring the ability of institutions to reliably and responsibly influence human behavior for the betterment of public health and the health of the environment.

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A Case Study of Harmful Algal Blooms in the South Atlantic States

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APPENDIX A. WEBPAGES IDENTIFIED

CDC	https://www.cdc.gov/habs/general.html
CDC	https://www.cdc.gov/habs/index.html
CDC	https://www.cdc.gov/habs/materials/index.html
CDC	https://www.cdc.gov/habs/materials/factsheet-cyanobacterial-habs.html
CDC	https://www.cdc.gov/habs/materials/factsheet-marine-habs.html
CDC	https://www.cdc.gov/habs/pdf/cyanobacteria_faq.pdf
CDC	https://www.cdc.gov/habs/pdf/algal_bloom_poster.pdf
CDC	https://www.cdc.gov/habs/pdf/habsphysician_card.pdf
CDC	https://www.cdc.gov/habs/pdf/habsveterinarian_card.pdf
CDC	https://www.cdc.gov/habs/pdf/ohhabs-fact-sheet.pdf
CDC	https://www.cdc.gov/habs/ohhabs.html
EPA	https://www.epa.gov/cyano-habs/learn-about-cyanobacteria-and-cyanotoxins
EPA	https://www.epa.gov/cyano-habs/causes-cyano-habs
EPA	https://www.epa.gov/cyano-habs/exposure-cyano-habs
EPA	https://www.epa.gov/cyano-habs/health-effects-cyanotoxins
EPA	https://www.epa.gov/ground-water-and-drinking-water/managing-cyanotoxins-public-drinking-water-systems
EPA	https://www.epa.gov/cyano-habs/epa-drinking-water-health-advisories-cyanotoxins
EPA	https://www.epa.gov/ground-water-and-drinking-water/summary-cyanotoxins-treatment-drinking-water
EPA	https://www.epa.gov/cyano-habs/cyanotoxins-and-safe-drinking-water-act-drinking-water-protection-act-contaminant
EPA	https://www.epa.gov/cyano-habs
FL	http://www.floridahealth.gov/environmental-health/aquatic-toxins/harmful-algae-blooms/index.html
FL	https://myfwc.com/research/redtide/taskforce/members/
FL	http://www.floridahealth.gov/environmental-health/aquatic-toxins/updates-report-and-contact/index.html
FL	https://floridadep.gov/AlgalBloom
FL	http://www.floridahealth.gov/environmental-health/aquatic-toxins/blue-green.html
FL	http://www.floridahealth.gov/environmental-health/aquatic-toxins/seafood-safety/index.html
FL	http://www.floridahealth.gov/environmental-health/aquatic-toxins/where-is-red-tide.html
FL	https://myfwc.com/research/redtide/taskforce/history/
FL	https://myfwc.com/research/redtide/taskforce/
FL	https://myfwc.com/research/redtide/general/harmful-algal-bloom/
GA	https://epd.georgia.gov/harmful-algal-blooms
GA	https://www.gachd.org/programs-services/environmental-health-2/harmful_algal_bloom_hab/
GA	https://www.gachd.org/programs-services/environmental-health-2/harmful_algal_bloom_hab/blue-green-algal-blooms/
GA	https://www.gachd.org/programs-services/environmental-health-2/harmful_algal_bloom_hab/red-tide-algal-blooms/
NC	https://deq.nc.gov/about/divisions/water-resources/water-resources-data/water-sciences-home-page/ecosystems-branch/algal-blooms
NC	https://www.ncwildlife.org/Portals/0/Conserving/documents/2015WildlifeActionPlan/NC-WAP_2015_ePDF_052016_chapters1-8.pdf
NC	https://www.ncwildlife.org/Portals/0/Conserving/documents/ActionPlan/WAP_Chapter5C.pdf
NC	https://www.ncwildlife.org/Portals/0/Boating/documents/Best%20Management%20Practices%20Manual%20for%20Marinas.pdf
NC	https://www.ncwildlife.org/Portals/0/Fishing/documents/PONDMAN5.PDF
NC	https://www.ncwildlife.org/Portals/0/Conserving/documents/ActionPlan/WAP_Chapter5_5A.pdf
NC	https://epi.dph.ncdhhs.gov/oe/a_z/algae.html

A Case Study of Harmful Algal Blooms in the South Atlantic States

NC	https://epi.dph.ncdhhs.gov/oeo/docs/HAB_Events_2005_2012.pdf
NC	https://epi.dph.ncdhhs.gov/oeo/algae/protect.html
NC	https://www.fws.gov/nwrs/threecolumn.aspx?id=2147591771
NC	https://www.albemarlercd.org/fighting-algal-blooms.html
NC	https://deq.nc.gov/about/divisions/water-resources/drinking-water
NC	https://www.ncwildlife.org/Portals/0/Fishing/documents/2019FishingDocuments/Pond-Management-Guide.pdf
NC	https://www.ncwildlife.org/Portals/0/Learning/documents/Profiles/mallard.pdf
NIEHS	https://www.niehs.nih.gov/health/topics/agents/algal-blooms/index.cfm
NOAA	https://oceanservice.noaa.gov/hazards/hab/
NOAA	https://www.noaa.gov/what-is-harmful-algal-bloom
NOAA	https://oceanservice.noaa.gov/facts/habharm.html
NOAA	https://oceanservice.noaa.gov/facts/redtide.html
NOAA	https://www.fisheries.noaa.gov/science-blog/phytoplankton-and-habs-sampling-2019-summer-survey
NOAA	https://www.fisheries.noaa.gov/monitoring-seafood-safety-and-coastal-ecosystem-health
NOAA	https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/habhrca/
RVKP	https://www.catawbariverkeeper.org/2019/08/15/algae-update/
RVKP	https://waterkeeper.org/magazines/be-the-change-volume-16/poison-blooms/
RVKP	https://waterkeeper.org/news/waterkeepers-florida-committed-to-protecting-sunshine-state/
RVKP	https://waterkeeper.org/news/florida-officials-urged-to-set-standards-to-protect-people-wildlife-from-harmful-algal-blooms/
RVKP	https://waterkeeper.org/news/a-chilling-message-keep-away-from-waters-edge/
RVKP	https://waterkeeper.org/news/suncoast-waterkeepers-sick-of-sewage-campaign-resolves-lawsuit-against-sarasota-county/
RVKP	https://waterkeeper.org/news/everglades-forgotten-northern-estuary/
RVKP	https://waterkeeper.org/news/lawsuit-launched-to-stop-toxic-algae-bloom-releases-from-lake-okeechobee/
RVKP	https://www.congareeriverkeeper.org/what-you-can-do
SC	https://www.scdhec.gov/environment/your-water-coast/harmful-algal-blooms
SC	http://dnr.sc.gov/water/aquaff/plankalgae.html
SC	https://www.dnr.sc.gov/news/2016/sep/sep6_algalblooms.html
SC	https://www.dnr.sc.gov/marine/mrri/envirom/pollution.html
SC	https://www.dnr.sc.gov/environmental/reportfishkill.html
SC	https://www.dnr.sc.gov/cwcs/pdf/Hardclam.pdf
SC	http://portal.dnr.sc.gov/marine/NERR/pdf/pondconference5-22-14/Powell_Aeration%20for%20Stormwater%20Ponds.pdf
USDA	https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd518784.pdf
USDA	https://www.ars.usda.gov/research/publications/publication/?seqNo115=93999
USDA	https://www.nal.usda.gov/waic/great-lakes-harmful-algal-blooms-and-hypoxia-agricultural-aspects
USDA	https://reecis.usda.gov/web/crisprojectpages/0209332-harmful-algal-blooms.html
USDA	https://nifa.usda.gov/announcement/mitigating-occurrence-harmful-algal-blooms
USDA	https://agresearchmag.ars.usda.gov/1999/jan/form/
USDA	https://portal.nifa.usda.gov/web/crisprojectpages/1006264-ensuring-food-safety-from-harmful-algal-blooms-and-cyanotoxin-risks.html
USGS	https://www.usgs.gov/centers/glri/science/harmful-algal-blooms-habs?qt-science_center_objects=0#qt-science_center_objects
USGS	https://www.usgs.gov/news/science-harmful-algae-blooms
USGS	https://www.usgs.gov/mission-areas/environmental-health/science/new-guide-help-identify-harmful-algal-blooms?qt-science_center_objects=0#qt-science_center_objects
USGS	https://www.usgs.gov/centers/oki-water/science/harmful-algae-blooms-habs?qt-science_center_objects=0#qt-science_center_objects
USGS	https://www.usgs.gov/centers/glri/science/harmful-algal-blooms-habs?qt-science_center_objects=0#qt-science_center_objects

APPENDIX B. HABITS CODEBOOK

BASIC INFORMATION

NOTE: 1=Yes, 0=No

1. Resource code:
2. Web link:
3. Author of webpage/PDF:
1=State Agency
2=National Agency
3=NGO

Publishing organization:

1. Title/heading of webpage/PDF:
2. Is there a date listed on the webpage/PDF?
1=Yes
0=No
 - a. If yes, what is the most recent date listed? (yyyy/mm/dd)
 - b. If yes, the date listed is the date that the website was:
1=Written
2=Posted
3=Updated
4=Unclear

FORMAT

6. Format:
1=Website
2=PDF
3=Available as both website and PDF
7. Is the webpage/PDF in paragraph form, bullet point form, or both?
1=Paragraph form
2=Bullet point form
3=Both
 - a. If webpage/PDF is in paragraph form, are subheadings used to “chunk” information?
1=Yes
0=No
8. Is text written in 2nd person (e.g. “you”)?
1=Yes
0=No
9. Is the F pattern utilized in terms of the most important information?
1=Yes
0=No
10. Are typographic cues (color, bold, size, background) used to emphasize key points?
1=Yes
0=No

A Case Study of Harmful Algal Blooms in the South Atlantic States

11. Is type text in a uniform typeface?

1=Yes

0=No

12. Is type size a reasonable readable size?

1=Yes

0=No

13. Do you have to click “next” or scroll through multiple pages in order to view the entire article/all of the information?

1=Yes

0=No

14. Does the page contain a glossary or definition of technical terms?

1=Yes

0=No

15. Are there less than 3 levels of information on the page?

1=Yes

0=No

16. Is there an option to receive a notification when the webpage is updated?

1=Yes

0=No

CONTENT

Focus Area = Minimum of 75% of page devoted to specific topic

17. Is the focus area of the webpage/PDF HAB biology and chemistry (including metrics like water temperature, pH, DO, etc.)?

1=Yes

0=No

18. Is the focus area of the webpage/PDF Public Health (human health impacts of a HAB)?

1=Yes

0=No

19. Is the focus area of the webpage/PDF Ecological (prevention or treatment of water)?

1=Yes

0=No

20. Does the webpage/PDF contain a warning about human exposure?

1=Yes

0=No

21. Does the webpage/PDF contain a warning about animal exposure?

1=Yes

0=No

22. Are freshwater or marine HABs addressed?

1=Freshwater

2=Marine

3=Both

4=None specified

23. Does the webpage/PDF mention temperature as an environmental factor contributing to HABs?

1=Yes

0=No

24. Does the webpage/PDF mention sunlight as an environmental factor contributing to HABs?

1=Yes

0=No

25. Does the webpage/PDF mention pollution as an environmental factor contributing to HABs?

1=Yes

0=No

26. Does the webpage/PDF mention weather conditions as an environmental factor contributing to HABs?

1=Yes

0=No

27. Does the webpage/PDF mention specific toxins?

1=Yes

0=No

a. If yes, what toxins are mentioned?

28. Does the webpage/PDF list ways to identify a HAB?

1=Yes

0=No

29. Does the webpage/PDF list specific activities to avoid if a HAB is suspected?

1=Yes

0=No

30. Does the webpage/PDF mention a specific disease or syndrome?

1=Yes

0=No

a. If yes, what disease(s)/syndrome(s) are mentioned?

31. Does the webpage/PDF mention a specific body of water?

1=Yes

0=No

32. Does the website/PDF contain an explicit call to action (e.g. Don't go in!)?

1=Yes

0=No

33. Does the website/PDF include a summary, review of the key messages, or takeaway points?

1=Yes

0=No

34. Does the webpage/PDF provide a phone number to call for more information?

1=Yes

0=No

A Case Study of Harmful Algal Blooms in the South Atlantic States

35. Does the webpage/PDF provide an email address to contact for more information?

1=Yes

0=No

36. Does the webpage/PDF include the name of a contact person?

1=Yes

0=No

37. Does the webpage/PDF include a mailing address for more information?

1=Yes

0=No

38. Is there a "Contact Us" link on the webpage?

1=Yes

0=No

39. Does the webpage/PDF include an option to "share" the information via social media or email?

1=Yes

0=No

40. Does the webpage/PDF provide any links to additional information that is relevant to our topic?

1=Yes

0=No

a. If yes, how many links are provided?

41. Is the webpage/PDF offered in other languages?

1=Yes

0=No

a. If yes, what language(s)?

42. Does the website have any pop-ups or advertisements?

1=Pop-ups

2=Advertisements

3=Both

4=Neither

5=Not applicable (for PDFs)

43. Is there a video and/or sound bite embedded in the website?

1=Yes

0=No

44. Does the website have any embedded links to social media accounts?

1=Yes

0=No

45. Is there a place to leave a comment or view others' comments about the website?

1=A place to leave a comment

2=A place to view others' comments

3=Both

4=Neither

46. SMOG calculation

IMAGES/DESIGN

47. Does the webpage/PDF include photos/illustrations?

1=Yes

0=No

a. If yes, is/are the image(s) of water?

1=Yes

0=No

b. If yes, is/are the image(s) of people?

1=Yes

0=No

c. If yes, is/are the image(s) of animals (fish, birds, aquatic mammals, dogs)?

1=Yes

0=No

48. Does the webpage/PDF include any other organizations' logo(s)?

1=Yes

0=No

a. If yes, which ones?