Environmental Change and Septic Systems in Nags Head: Local Perspectives and Impacts on Water Quality and Quantity

University of North Carolina at Chapel Hill
Institute for the Environment
Outer Banks Field Site
Fall 2018
Capstone Report

December 13, 2018

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Acknowledgments

Special thanks to the faculty and staff of the Outer Banks Field Site (OBXFS):
Andy Keeler, Linda D'Anna, Lindsay Dubbs, Corey Adams

The Community Advisory Board: Christin Brown, Nellie Dixon, Fay Davis Edwards, Erin Fleckenstein, Kate Murray Jones, Jaye Massecar, Aaron McCall, Rhana Paris, Matt Price, Kipp Tabb, Hadley Twidd, Heidi Wadman

Our internship mentors:
Jennifer Karpowicz Bland – Dare County District Attorney's Office
Karen Clark – Outer Banks Center for Wildlife Education and Wildlife Resources Commission
Herbert Council – Can Stand OBX L.L.C.
Ann Daisey – Dare County Soil and Water Department
Warren Eadus – Quible and Associates P.C.
Sara Hallas – NC Coastal Federation
Kate Jones – NC Coastal Reserve and Estuarine Research Reserve
Aaron McCall – The Nature Conservancy
Mellissa Dickerson – The Town of Manteo
Jessica Taylor – OBX Center for Dolphin Research
Sam Walker – OBX Voice and Jam Media Solutions
Holly White – The Town of Nags Head

Community members, guest speakers and businesses who contributed to our experience: Robbie Fearn (Audubon Pine Island Sanctuary); Kim Armstrong, Reide Corbett, Jeff Gottermeyer, Haley Grabner, Mike Hosey, Jeff Lewis, Marie Magee, Robert McClendon, John McCord, Mark Stancill, and Dave Sybert (Coastal Studies Institute); Meghan Agresto (Currituck Lighthouse); Ryan Bower (Dare County Water Department, Kill Devil Hills Desalination Plant); Alex Manda (East Carolina University); Lora Harris (Chesapeake Biological Laboratory, University of Maryland); Baxter Miller and Ryan Stancil (Stancil Miller & Co.); Bryan Giemza (Southern Historical Collection, University of North Carolina); Ken Partlow and Rick Probst (Jennette's Pier););Lindsay Usher (Old Dominion University); Justin Barnes (Jockey's Ridge State Park); Melinda Lambert, Adam Simon, and T. D. VanMiddlesworth (North Carolina Division of Marine Fisheries); Sara Mirabilio (North Carolina Sea Grant); O'Neal's Sea Harvest (Wanchese, NC); the North Carolina Aquarium on Roanoke Island; Sharon Meade (Outer Banks Center for Wildlife Education); Roy Porter and Envirochem (Wilmington, NC); Todd Krafft, Andy Garmin, Cliff Ogburn, David Ryan, and Holly White (Town of Nags Head); Violet Anderson, Myra Burke, Jaye Cable, Chrissie Greenberg, Evelyn Johann, Cory Keeler, Jason Kinnear, Jing Lui, Dawn Morgan, Mike Piehler, Rusty Rogers, Suzanne Rucker, and Charu Vengavayal (University of North Carolina at Chapel Hill); Kenny Midgett (Wanchese Trawl and Supply Company); George Wood and Environmental Professionals Inc. (Kill Devil Hills, NC)

Thank you to all the community members and participants that volunteered their time and thoughts to our capstone project!

Abbreviations

CAB: Community Advisory Board
Count: number of samples
CSI: Coastal Studies Institute
DEM: Digital Elevation Model
DST: Defined Substrate Technology
DTGW: Depth to Groundwater
E. Coli: *Escherichia coli*
GCMS: Gas Chromatograph Mass Spectrometer
GW: Groundwater
HDPE: High Density Polyethylene
HPLCMS: High Performance Liquid Chromatograph Mass Spectrometer
Min: minimum
Max: maximum
MPN: Most Probable Number
NC: North Carolina
NH: Nags Head
NHFS: Nags Head Fire Station
NTU: Nephelometric Turbidity Unit
OBXFS: Outer Banks Field Site
OF: Outfall
OWTS: Onsite Wastewater Treatment System
PPCP: Pharmaceuticals and Personal Care Products
StdDev: Standard Deviation;
SW: Surface water
YSI: Yellow Stone Instrument

Abstract

The Outer Banks is a chain of barrier islands off the coast of North Carolina that separates the Atlantic Ocean from the mainland. The islands are surrounded by water and have a unique hydrology due to the interconnection of groundwater aquifers, sound, and ocean. Forces driven by global climate change - particularly sea-level rise - coupled with human development have resulted in increased flooding and deteriorating surface-water quality. Approximately 80% of the town of Nags Head uses septic tanks to treat its wastewater with septic systems, and septic systems that are poorly maintained or fail can leach nutrients and bacteria into groundwater reservoirs that ends up in the Sound and Ocean. The threat of degradation of water quality, particularly due to septic leachate, will have ecological and anthropogenic effects on the Town of Nags Head, its residents, and its visitors. To contribute to the understanding of local perspectives and impacts of environmental changes and septic system in Nags Head, quantitative and qualitative natural and social science approaches were employed to investigate the likelihood of septic leachate in water reservoirs and local perspectives of water quality and quantity.

Change in water level over different time scales and across the landscape was investigated by analyzing historical data on depth to groundwater data collected by the Town from 2011 to 2017. Water level in each water year changed relative to the seven-year median water level with precipitation across all sampling locations. We did not see an increase in water level in the summer, corresponding to increasing water use mediated fluxes of water from the confined drinking water aquifer to the groundwater aquifer, as expected. We also determined that the water level exceeded the depth that would keep it sufficiently separated from the depth of septic drainfields to allow for the recommended amount of percolation through unsaturated soils and natural treatment for contaminant removal on 49% of sampling occasions. The overall trend in the data is that water level has increased over time, and although our dataset is shorter than that required to attribute the increase in water level to sea level rise, we expect sea level rise will continue to increase the water level of this coastal town, further shrinking the separation between groundwater and septic drainfields, thereby posing increasing risks to water quality.

Using previously compiled data as a foundation, our analysis of historical data from the area was compared with water samples taken from three surface-water drainage ditches, two groundwater wells, and one ocean outfall pipe. To determine if there was significant interaction between groundwater and surface-water reservoirs and septic leachate, the samples were tested for nutrients, bacteria and the presence of caffeine. In general – but with a high degree of variability – the data suggest that storm events lead to increased interactions between septic system leachate and surface-water reservoirs, resulting in noticeable increases in nutrients like ammonia, nitrate/nitrite nitrogen, as well as *E. coli* and *Enterococcus* cell counts. The presence of significant levels of caffeine at one of our surface-water sampling sites points to interactions with septic system leachate, but at other sites only trace levels of caffeine were found. The high variability in the data means that the level of surface-water contamination was spatially inconsistent and that the higher levels of contamination at certain sampling sites were likely due to some point-source pollution like animal waste or nearby leaking systems. The presence of significant levels of caffeine at one of our surface-water sampling sites points to interactions with septic

To understand how Nags Head residents' perspectives regarding changing environmental conditions, water quantity, and water quality we conducted 27 semi-structured interviews with property owners. We found that participants valued the waters of Nags Head for various reasons,

including aesthetics, recreation, community, and livelihood. These connections to water positioned study participants to notice and report on a variety of environmental changes and concerns. They postulated that exacerbated flooding, decreased water quality, and increased pollution in water reservoirs were due to increased frequency and intensity of storms, more intensive development, and the management of stormwater and wastewater. Further analysis revealed concerns about a potential downward spiral wherein the economy of Nags Head was reliant on tourism, tourism pushed for more development, development decreased water quality, and poor water quality would impact economy and tourism. Analyses also disclosed that though septic systems were preferred over central sewage, this opinion was largely due to financial and logistical concerns. Overall, we noted several knowledge gaps among participants regarding water quality and wastewater treatment. There existed no central information source, which inhibited their ability to take individual responsibility for septic tank maintenance. Additional efforts by the town of Nags Head to fill these gaps seem warranted. of

Table of Contents

Introduction

Coastal social, economic, and environmental systems are dynamic and are vulnerable to threats posed by global-scale environmental changes, such as sea-level rise, flooding, and increased storm prevalence (USGCRP, 2018). On both local and global scales, changing environmental conditions will impact coastlines, with broad implications for coastal communities in all parts of the world. Local environmental changes will be exacerbated by increasing human populations and subsequent development. Coastal communities will face a host of decisions about how to adapt to new and changing circumstances, including higher water tables, saltwater intrusion, and enhanced erosion with concomitant inundation. These changes in how water moves across coastal landscapes will likely affect the viability of human infrastructure, such as roadways and wastewater treatment. In some cases, current wastewater treatment practices may become so compromised that wastewater streams may regularly mingle with the surface and groundwater, leading to human and environmental health concerns. Our study investigated the effects of sea-level rise, flooding, development, and resultant changes to water quantity and quality in the barrier island community of Nags Head, North Carolina (NC), a coastal town located in Dare County, part of the Outer Banks region of NC.

The following section provides a preliminary overview of coastal hydrology in the Outer Banks, detailing the relevant water reservoirs and fluxes. Then, we discuss the relationship between hydrology and human populations along the coast, with particular emphasis on increasing population size and development. Next, we elaborate on how water quality and quantity are influenced by these environmental changes, focusing on those which affect wastewater treatment in Nags Head specifically. Then, we summarize potential adaptations for wastewater treatment to environmental changes and their consequences, highlighting innovations put in place by the Town of Nags Head in light of water quality and quantity concerns. This is followed by a discussion of coastal resident perceptions, behaviors, and adaptations in response to environmental changes.

Coastal Hydrology

The Hydrological Cycle and the Outer Banks

To begin to address how changing environmental conditions affect water quantity and quality in Nags Head, one must first understand how and where water is retained in different reservoirs and how it moves across the landscape and between reservoirs under normal conditions. Water is present in various global reservoirs including the atmosphere, on the surface of land (as ice, snow, and surface-water such as lakes and rivers), in biota, below the surface of land (as confined aquifers and unconfined groundwater aquifers), and in sounds and oceans. These reservoirs and the fluxes between them, including evaporation, transpiration, precipitation, and river flow, are referred to as the hydrological cycle (Figure 1; Chahine, 1992). Importantly, liquid fluxes between surface-water, groundwater, and ocean reservoirs not only transport water, but also a host of dissolved and suspended compounds and particles, including nutrients, bacteria, and pollutants.

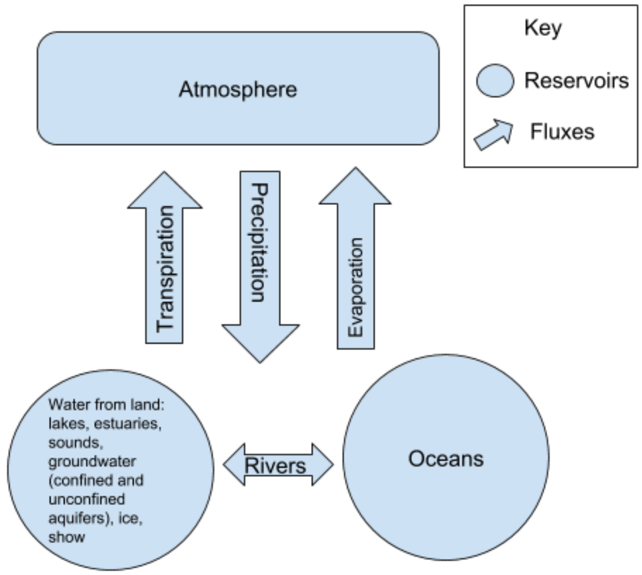

Figure 1: Basic diagram of the hydrological cycle, depicting global reservoirs and the fluxes of water that move liquid and gaseous forms of water between them (adapted from Chahine, 1992).

Outer Banks Hydrology: Reservoirs and Fluxes

The islands of the Outer Banks of North Carolina are surrounded by water and have distinctive hydrological characteristics. The important water reservoirs for this area include the Atlantic Ocean, the freshwater and brackish sounds of the Albemarle-Pamlico estuarine system, groundwater located in the surficial unconfined aquifer below the water table, surface-water, and the brackish confined Tertiary-age Yorktown aquifer, from which water is withdrawn for household use in the northern Outer Banks (Flatt, 2014). The freshwater surficial unconfined groundwater aquifer and surface-water are fed by local rainfall infiltration. These aquifers connect to the ocean and sounds through horizontal and vertical percolation (Dolan, 2016). Figure 2 illustrates this relationship by depicting a cross-section of the coastal landscape. The sizes of the aquifers fluctuate due to anthropogenic and natural forces. For instance, greater rainfall results in more water in the unconfined groundwater aquifer and surface-waters, while pumping the groundwater aquifer to the sounds or ocean reduces the amount of water it contains (Dolan, 2016).

Tides, waves, and storms are other critical components of Outer Banks hydrology. These forces influence the shape and stability of coastal landscapes by shifting sediment and eroding or nourishing a shoreline (Frankenberg, 1997), thereby shifting the relative bounds of the groundwater aquifer and the ocean and/or sounds. Precipitation associated with storms may also result in abundant stormwater runoff that either flows to the ocean and sounds (Dolan, 2016) or accumulates in the unconfined groundwater aquifer, which, when saturated, causes flooding of the relatively flat landscape. On the Outer Banks, a stormwater drainage system consisting of open and closed drainage ditches and outfall pipes is meant to transport stormwater runoff directly to the ocean and sounds quickly to reduce flooding. The lower elevation drainage ditches often contain water between storm events, thereby creating an additional surface-water reservoir.

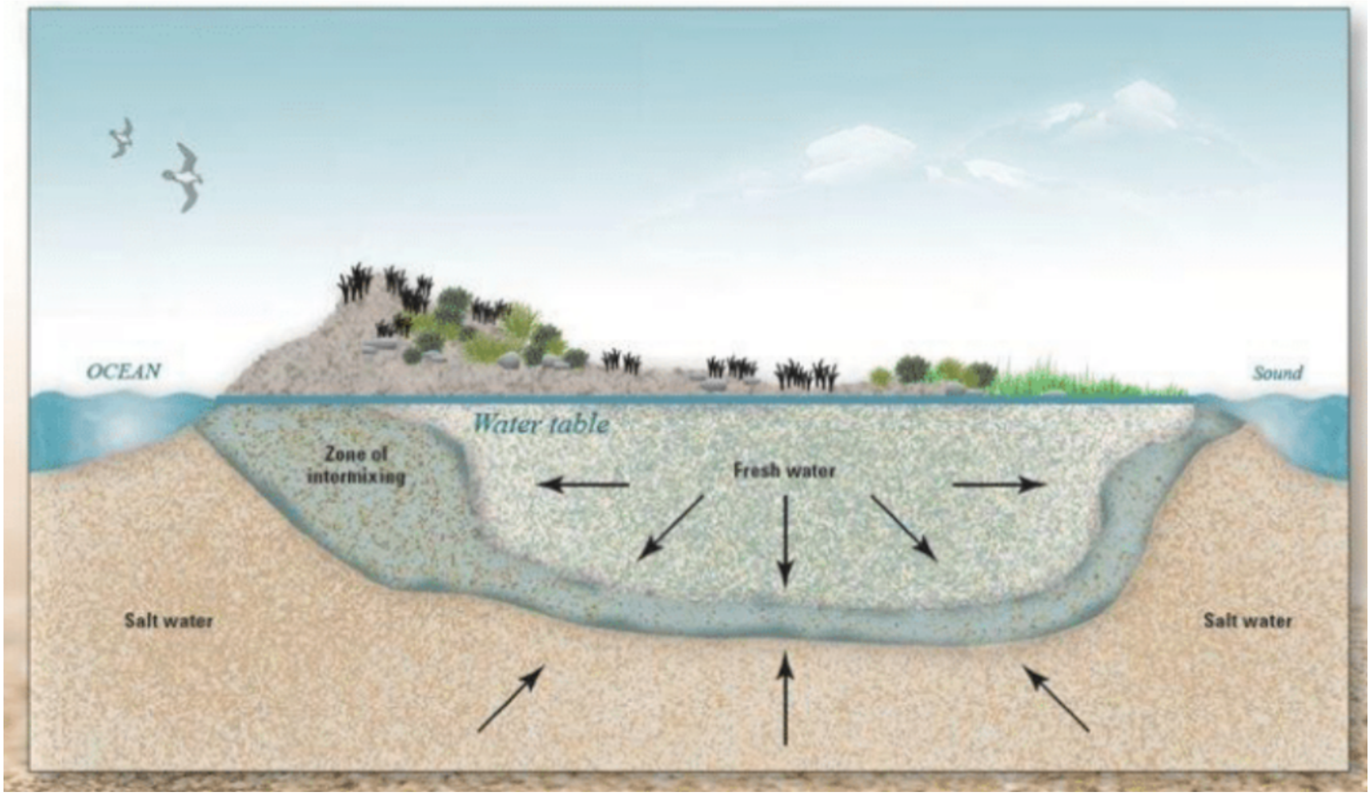

Figure 2: Water movement through a barrier island system (reproduced from Dolan, 2016).

The Socio-Hydrological Cycle

The fluxes between the hydrological reservoirs are further complicated by change and human development. The physical, geological, and ecological dimensions of the hydrological cycle on the Outer Banks are intimately connected to its social systems and external environmental factors. We can refer to this interrelationship as a socio-hydrological cycle (Figure 3; Baldassarre, 2017). Community responses to environmental changes like sea-level rise and flooding are impacted by both individual and collective local perceptions and beliefs. Resultant decisions and policies to address flooding or impacts of sea-level rise influence the effects that future storms, flooding events, and sea-level rise have on the community and individuals. A socio-hydrological approach incorporates ecological change and anthropogenic development into our understanding of hydrology. This is critical in coastal systems where the impacts of sea-level rise and increased storm events are complicated by coastal population growth, increases in impervious surfaces, and greater wastewater production.

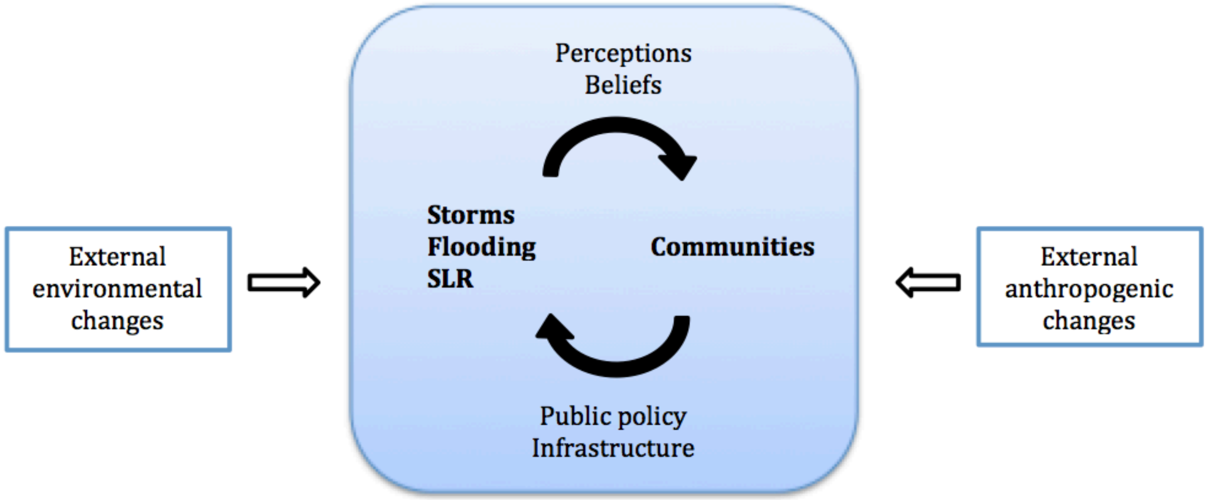

Figure 3: The Socio-Hydrological Cycle: Both environmental and anthropogenic influences affect the relationships between communities and environmental change relative to water reservoirs and fluxes (adapted from Baldassarre, 2017).

Coastal Changes: Water Level and Water Quality Implications

Coastal Population Patterns and Impacts on the Environment

Globally, population migration trends are clear; migrations are occurring in greater numbers from rural areas to urban areas, with individuals seeking employment, better access to resources, and other advantages associated with a more connected world. Many of these urban areas are located on coastlines, prompting many geographers and scientists to predict a substantial global migration from inland areas to the coast over the course of the twenty-first century. Using current population trends, one study predicted that by the year 2060, low-elevation zones, specifically coastal areas, could host as many as 1.4 billion people, up from 625 million in the year 2000 (Neumann et al, 2015). This would represent about 12% of the world's projected population of 11.3 billion people for 2060 (Neumann et al, 2015). While the researchers found that most of these coastal population increases would occur in Asia and Africa, they found that the same trend would likely occur in North America, though to a lesser extent. This correlates with past data from the United States Census Bureau that has tracked increases in coastal populations on American coastlines. Despite being the least populated coastal region in the country, the southeast coastal United States, stretching from south Florida to the North Carolina-Virginia border, experienced the most rapid population growth of any other coastal region between 1980 and 2008 (Crossett et al, 2004). In particular, Dare County experienced a 10.1-15.0% increase in its permanent population of residents from 2003 to 2008.

Population growth in coastal settings is often tied to environmental degradation (Crawford, 2007). Coastal development in the form of more commercial infrastructure and residential housing can disturb the environment and affect coastal hydrology in myriad ways. Deforestation and the clearing of wetlands for development leave less land to absorb precipitation or storm surge in the groundwater reservoir, while an increase in impervious surfaces, such as parking lots and houses, further hinders absorption. This can increase the risk and the extent of flooding during rain events, as the water cannot infiltrate into the ground.

Without wetlands and forests to act as natural buffers, increasing water levels on the land surface due to storm surges may be exacerbated.

Water Quantity and Flooding

Environmental changes attendant with coastal population growth are layered onto a dynamic landscape that is changing on both small and broad spatial and time scales, from daily tidal changes to global climatic shifts. Although the annual extent of sea-level rise is perhaps seen as minor and may go unnoticed by the general public, the consequences of elevated water levels will perhaps be the most damaging to coastal areas, but especially to barrier islands, such as the Outer Banks. A monitoring location in the coastal town of Duck, NC, has collected data from 1978 to 2017 to depict monthly mean sea-level trends. The relative trend of increase is 4.55 millimeters (0.18 inches) per year, which can be equated to a change of 1.49 feet in 100 years (NOAA, 2014). Each year, as positive-feedback cycles continue to raise global temperatures, and land-based ice continues to melt, these trends may continue or become exaggerated (Vitousek et al. 2017). When considered in conjunction with waves, tides, and storm surges, sea-level rise will likely cause devastating inundation of low-lying coastal areas in the coming decades. Further, extreme precipitation events have increased and are predicted to continue to increase throughout the Southeastern region of the United States, as the number of days with more than three inches of precipitation has increased during the years 1900 to 2016 (USGCRP, 2018). Combined, changes to precipitation patterns and flooding frequency pose severe threats to coastal communities.

The monetary cost of more frequent and spatially extensive flooding will impact home-owners and business-owners in flood-vulnerable areas. Not only are flooding mitigation practices expensive, but taking preventative measures to reduce the effects of flooding can be particularly burdensome to property owners and local governments. The damage from flooding in major coastal cities around the world is estimated to cost more than $1 trillion by 2050 (Negro, 2013). These costs will be incurred by the citizens either directly, by individually paying for preventative mitigation or clean-up measures, or indirectly, through taxation and public spending.

Water Quality and Tourism

In addition to affecting water quantity, coastal development and environmental changes also affect water quality by introducing pollutants, such as nutrients, bacteria, and chemicals. The contamination of water reservoirs, including those used recreationally, poses a major threat to the ways in which water resources are utilized on coastlines. Tourism is a major industry for the Outer Banks, employing over 13,000 individuals and resulting in more than $100 million in expenditures in the year 2017 (Visit North Carolina, 2018). A major draw for many visitors and residents alike is the water itself for its recreational, commercial, and aesthetic values. A number of pollutants pose hazards to both human health and to the ecological health of the region. Contamination or degradation of coastal water reservoirs could reduce tourist presence and revenue in the region.

Many coastal areas experience water quality issues as a result of stormwater runoff (Schiff et al. 2015). As this water flow increases due to the expansion of impervious surfaces and development, the water quality along the coast will suffer. Importantly, human development also creates an additional reservoir and set of fluxes in the socio-hydrological cycle: wastewater and its flow to groundwater, surface-water, sounds, and ocean reservoirs. We define wastewater as water that has been used in homes and businesses and then discarded through drainpipes. Effective treatment of wastewater is critical to protecting human and environmental health within coastal systems, yet the dynamic nature of these systems and environmental changes to the socio-hydrological cycle can interfere with effectively treating wastewater to remove pollutants.

Wastewater, Wastewater Treatment, and Coastal Systems

In the United States, more than one in five households rely on onsite wastewater treatment systems (OWTS) to treat and dispose of their wastewater, as opposed to centralized wastewater treatment in the form of a public sewer system connection (EPA, 2018). OWTS are comparatively low-cost and non-energy intensive means of effectively treating wastewater and protecting water quality (EPA, 2018). However, when OWTS are not properly installed or maintained, they can contribute to environmental degradation and public health concerns (EPA, 2018).

Septic tank systems are a type of OWTS. They are relatively simple structures that are often found in rural areas, outlying suburbs, and locations distant from centralized sewage. They are customizable in size and can be used by variously sized households and businesses in a diverse range of locations, both inland and on the coast (Mallin, 2013). A septic tank system has two main components: the septic tank itself and the drainfield (Figure 4; Smart Growth). When you flush a toilet in your house, or when you use the water faucet to wash dishes, for example, water will exit your house as wastewater. This water runs through the main drainage pipe and enters the septic tank. Septic tanks are typically buried containers, which allow solids to settle to the bottom of the tank, while oils and grease rise to the top. Inside the tank, anaerobic bacteria break down the organic solids in the wastewater. When additional wastewater enters the tank, some of the liquid wastewater, or effluent, will exit from the other side of the tank, entering a distributional box before being distributed evenly through a system of pipes into the drainfield (Stone Environmental, Inc., 2005). As the effluent percolates through the soil of the drainfield, aerobic bacteria in the soil kill some of the remaining harmful components in the effluent (Septic 101, 2016).

Septic systems can be compromised when the soil in the drainfield becomes oversaturated. Effluent entering a saturated drainfield from the septic tank cannot percolate and will accumulate on the surface. Instead of being filtered, pathogens, bacteria, and nutrients in the effluent remain at the surface where humans and other organisms can come into contact with them. Soils in the drainfield can become oversaturated when the water table rises due to precipitation influxes or sea-level rise. A study on Cape Hatteras National Seashore found evidence that septic leachate may already be contributing to increased levels of fecal bacteria in ocean water due to runoff from lawns and roads after storms (Mallin et al., 2012). In a study conducted in Beaufort County, NC, Humphrey et al. (2013) determined that OWTS contributed to groundwater nitrogen levels. This kind of contamination from septic systems is exacerbated by frequent and/or heavy precipitation (Beal et al., 2005). If coastal populations increase without implementing updated wastewater treatment technologies, there is potential for deleterious impacts on public health, as septic systems may become overused and leach biologically hazardous effluent into the ocean, sound, surface-water, and groundwater reservoirs.

Septic Systems and Environmental Pollutants

Contaminants associated with septic systems affecting surface-water and groundwater quality include inorganic nutrient pollution, including ammonia, nitrate, and phosphate, as well as organic contaminants, metals, chemicals, and fecal bacteria (Canter and Knox, 1991). Determining whether or not contaminants found in surface-water and groundwater are the direct result of septic contributions is complicated by other sources of some of these contaminants within the system. This includes contaminants such as bacteria introduced by animal waste, from either pets or wildlife, or nutrients stemming from lawn fertilizers. Presence of chemicals that are unique to human wastewater, such as caffeine, artificial sweeteners, or chemical detergents, in surface-water or groundwater indicate water contamination attributable to septic systems, since these chemicals would not be found in the environment from non-septic sources (Richards, 2017). Previous studies have shown evidence of septic systems contributing contaminants to the surrounding environment when considering the effects of environmental factors (e.g. Cooper et al., 2016, Richards et al., 2015).

There are multiple significant reasons to be concerned regarding the presence of excess nutrients within water reservoirs. Research has shown that nitrogen, in particular, among other nutrients, such as phosphorus and carbon, can be an important limiting nutrient for primary production and, in excess, contributes greatly to eutrophication within coastal systems, threatening the function of ecosystems by deteriorating water quality (Howarth et al., 2006). Reduction in the function of these ecosystems could limit the ecosystem services they provide and could harm the overall health of the environment. Regarding bacterial contaminants, it is imperative to consider the effects of fecal bacteria in surface-water and groundwater reservoirs, since bacterial presence can increase the risk to humans and animals of contracting pathogen-based illnesses (Noble et al., 2004). Public and environmental health concerns resulting from these contaminants are critical to consider.

Maintaining Septic System Health in Nags Head, North Carolina

Septic systems have a large potential for water contamination, especially in areas such as the Outer Banks, where they are common and concentrated in relatively close proximity to one another. Individual home and business owners privately manage septic systems on their properties in Nags Head and many other locations. Caring for an existing septic system is important in order to maintain environmental quality and prevent contamination of surrounding soil and groundwater. It is the property owner's responsibility to maintain the health of their septic system, and there are tasks that are required for upkeep. The US Environmental Protection Agency (2002) recommends that septic systems be inspected every three years and that tanks be pumped as needed, typically every three to five years. Efficient water use and careful disposal ensure that the system is not damaged with foreign materials, such as cigarettes and large food waste, while drain fields can be properly maintained by limiting overlying construction and ensuring sufficient drainage (US EPA 2002).

The Town of Nags Head has employed measures to assess and encourage septic system maintenance within the municipality by implementing the Septic Health Initiative. This voluntary program began in 2000 and works to improve septic health through public education, comprehensive tank inspections and pumping, and monitoring of groundwater and surface-water quality (Town of Nags Head, date unknown). The Septic Health Initiative covers all OWTS that process fewer than 3,000 gallons of wastewater per day. Through the initiative, homeowners and businesses can acquire voluntary septic system inspections and receive loans for needed repairs or replacements. Education and outreach aimed at homeowners and businesses on the importance of upgrading outdated OWTS and/or elevating them in compliance with recommendations are important to avoid groundwater contamination (Stone Environmental, Inc., 2005).

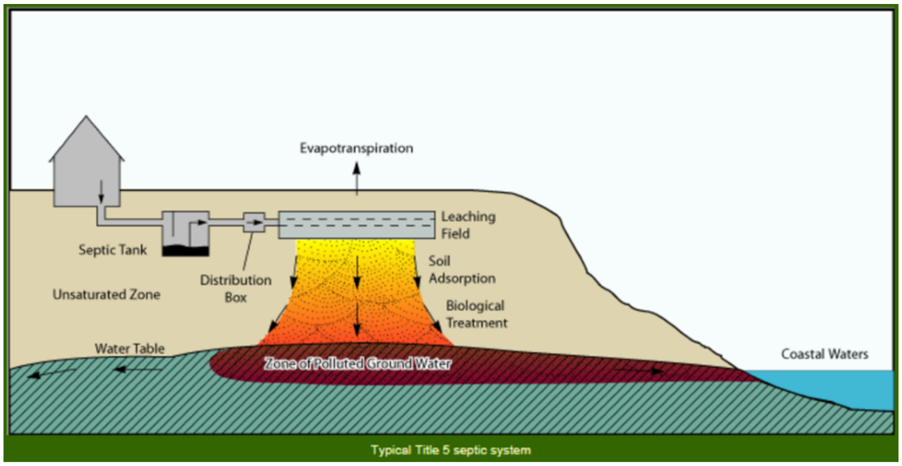

Figure 4: Schematic depicting septic system structure and processes as they relate to the surrounding environment (Smart Growth).

Adaptation Measures

In the face of environmental change, it is important to consider adaptive alternative methods of wastewater treatment and other measures to prevent the spread of contaminants between water reservoirs. Decisions regarding adaptation to change, including practicing low-impact development, lowering groundwater, and implementing centralized treatment, involve considering the logistical feasibility, financial concerns, and environmental impacts of alternative options.

Low-Impact Development

Low-impact development refers to stormwater management technologies that are rapidly being adopted by state and local governments to address increasingly extreme precipitation events and subsequent runoff in developed areas (Clar et al., 2015). Low-impact development includes installing structures like rain gardens, green streets and roofs, and hardscapes (Clar et al., 2015). Rain gardens, bunches of perennial plants and native shrubs planted in ground depressions, and green streets, streets bordered by permeable sidewalks and mature trees, control stormwater by collecting and filtering it through plants and soil rather than allowing it to run off impermeable surfaces and cause flooding. Green roofs provide storage, infiltration, and evaporation of rainfall and capture runoff in a manner similar to rain gardens, but can be installed on existing roofs to provide these services in already developed areas (Clar et al. 2015). Low-impact development techniques are suitable for areas that rely on septic systems as the wastewater treatment of choice since septic system functionality depends on soil saturation. If stormwater is not managed effectively, soils remain saturated and hinder septic system performance.

Groundwater Lowering

In coastal areas like Nags Head, when water levels rise, the distance between the septic drain fields and the groundwater table shrinks. The smaller this distance is, the less time and space the wastewater has to interact with soil and soil bacteria, meaning that the septic system and filtration are both less effective. One way to combat this problem is by physically lowering the groundwater table, thereby allowing septic effluent to filter through more sediment before reaching groundwater. There are several means of groundwater lowering, including pumping or implementing drainage systems that empty into lower elevation reservoirs. Lowering the groundwater table also allows the water contacting the ground during precipitation events and flowing through stormwater ditches to percolate deeper into the soil before reaching the groundwater table, delaying or preventing soil saturation and run-off.

Historically, the technique of groundwater lowering has been used for projects ranging from reducing earthquake damage to efficiently harvesting coal bed methane. A single large-diameter electrical submersible pump, typically used to clear water from coal seams, can pump greater than 150,000 gallons of water per day (Hashimoto and Yasuda 2016; Thakur et al. 2014). Although it would be technologically feasible, lowering the groundwater table in the town of Nags Head would be a financially burdensome and energy-intensive way to reduce the interactions between the groundwater and septic system effluent. The immediate benefits of this strategy would include desaturation of the soil near the surface, creation of increased space for water to percolate through, and reduced septic system failure.

Centralized Sewage Treatment

Not all OWTS locations have soil that is suitable for septic system drainfields. In some locations, the water table may be too high relative to the soil surface where septic systems would be installed. For this reason, there have been alternative onsite systems employed, such as using sand, peat, or plastic media in raised drain fields to aid in the treatment of wastewater in the place of soil. This process, known as biofiltration, can be efficient, as it does not require highly trained personnel to maintain and can instead be maintained by the property owner themselves. A study in India looked at the benefits of using an anaerobic onsite filter-based package system as an alternative to septic, and found it to be low-cost and extremely efficient at removing waste and pathogens (Sharma and Kazmi, 2015).

Centralized sewage treatment is another alternative to septic systems. This consists of a single plant that treats wastewater for an entire town or smaller area, such as a neighborhood. Unlike individual septic systems, they require electricity in order to filter the water, and do not rely on the individual households to properly maintain their wastewater treatment systems. They are typically farther away from residences, which lessens the chance of pollutant contamination and odor problems. There are also high costs and massive infrastructure changes associated with centralized sewage that would present challenges if Nags Head were to make the change from OWTS to a centralized system.

Perspectives on Wastewater Treatment and Environmental Change

Effectively adapting wastewater treatment will require coordinated decision-making among individual property owners, local governments, and state and federal agencies. Before such efforts are implemented, a clear understanding of how residents perceive issues related to wastewater and changing environmental conditions is needed. These perceptions are part of the socio-hydrological cycle (Figure 3) and they directly influence decision-making. Residents' attitudes, behaviors, knowledge gaps, and concerns about the consequences of ineffective wastewater treatment are critical information for adaptive strategy development.

Only limited research related to resident and homeowner perceptions, behaviors, and knowledge regarding wastewater and septic tank systems exists. We know even less about homeowner perspectives on the potential interaction between wastewater treatment decision-making and shifting environmental factors. Findings obtained in a variety of locales have indicated that homeowner knowledge and awareness of septic tank systems is largely limited (e.g. Schwartz et al. 1998; Fizer 2016). Brownlie et al. (2015) examined pro-environmental behaviors of residents with OWTS in the United Kingdom and found that the majority of respondents felt personally responsible for maintaining the system. This suggests that the inefficiency and detrimental impacts of these systems could largely be mitigated by better equipping residents with information about proper maintenance of septic systems and their associated environmental impacts. In addition, mitigation could be achieved by identifying appropriate resources and incentives for residents to adapt their OWTS in response to changing environmental conditions (Brownlie et al., 2015). Another study suggested that water quality was considered a 'common good' resource shared within a community, and as such, the local government should bear the responsibility of handling water quality issues like wastewater contamination (McSwain, 2006).

The relative weighting of residents' expectations about individual responsibility compared to community or governmental responsibility for managing the risks associated with wastewater treatment failure and poor water quality will inevitably vary across coastal communities. These expectations may be related to a variety of factors that influence perceptions of the severity and likelihood of these risks, including awareness of coastal change, its implications for septic system function, and personal experiences of flooding and septic failure (Devitt et al., 2016). Understanding these perceptions is critical to engaging residents in effective decision-making and behaviors around wastewater treatment that will be adaptive to continuing change in coastal systems.

Our Study

Our project's goal is to understand how changes to the socio-hydrological cycle, including climate-driven factors, affect key aspects of water quantity and quality in Nags Head, NC. We used two distinct approaches to shed light on this question: a natural science approach, including water level and quality sampling and data analysis, and a human dimensions approach based on interviews to determine stakeholder perspectives. We then integrated the results to gain insight into our overarching question regarding changes to the socio-hydrological cycle.

For the human dimensions component of our study, we took a qualitative approach to characterize Nags Head residents' perceptions about coastal waters, flooding, wastewater treatment, and changing environmental conditions, with a focus on the Gallery Row sub-watershed. We aimed to understand how participants conceptualize the quality of surface-waters, the impacts of storm- and flood-waters, and the integrity of onsite wastewater treatment systems in the context of a changing coastal environment. We were interested in identifying any gaps in knowledge about onsite wastewater treatment methods and maintenance, as well viewpoints regarding responsibility for wastewater management.

The natural science and hydrology research was composed of two major components: examining how groundwater levels have changed over time and understanding how surface-water quality is affected by storm events. We analyzed data collected from groundwater wells by the Town of Nags Head from 2011 through 2017 to examine the changes in groundwater levels across the landscape of Nags Head. We hypothesized that the groundwater level changed over time as a result of anthropogenic changes to the hydrologic cycle. We anticipated short-term changes to include higher groundwater levels and higher surface drainage ditch water levels in low-lying areas due to runoff from impervious surfaces. We also expected seasonal variability in groundwater levels as a result of increases in household water use, which takes water from the confined groundwater aquifer and transfers it to the unconfined groundwater aquifer via wastewater disposal, during the height of summer tourism. The historical dataset we accessed was shorter than the thirty-year record advised to discern a long-term rise in groundwater level expected as a result of sea-level rise. However, we also examined the changes in groundwater level from 2011 to 2017 to assess a long-term pattern of increasing groundwater level attributable to the rising ocean pushing water in the unconfined aquifer under Nags Head closer to the surface.

Our second hydrological research direction was a field-based study aimed at exploring how water quality changed during and following storm events. We hypothesized that we would see a spike in bacteria and nutrient concentrations in the surface-water sampling sites following storm events. We expected this to occur as the result of a combination of the following two fluxes: run-off of water containing nutrients and animal feces contaminating surface-water in ditches; and leachate from septic system drainfields mixing with groundwater and surface-water in drainage ditches as a result of soil saturation. This field study will also serve as the “before” component of a Before-After-Control-Impact (BACI) analysis to determine the efficacy of a groundwater-lowering engineering modification of an ocean outfall pipe in the Gallery Row sub-watershed. This modification is intended to lower groundwater and prevent flooding, but will also perhaps improve water quality. We encourage subsequent research to include the “after” component of the proposed BACI we have begun here.

Methods

Study Site

To better understand water level and water quality challenges within the Town of Nags Head, we worked with the Town to identify a sub-watershed where flooding was regular and groundwater lowering engineering modifications were planned for the near future. We thus selected the Gallery Row sub-watershed for our field-based hydrological and human dimensions components of our study (Figure 5). We sampled six locations for the field-based water quality study. Two of the sites were groundwater wells: one located in the Nags Head Woods, the other at the end of Lookout Street near Jockey's Ridge State Park. We also collected data and samples from three surface-water drainage ditches: two of these located on S. Memorial Avenue, and one just south of the Red Drum Taphouse restaurant. Lastly, we sampled the Gallery Row Ocean Outfall, which is south of the East Gallery Row beach access. Table 1 shows the geographic coordinates of the sampling locations.

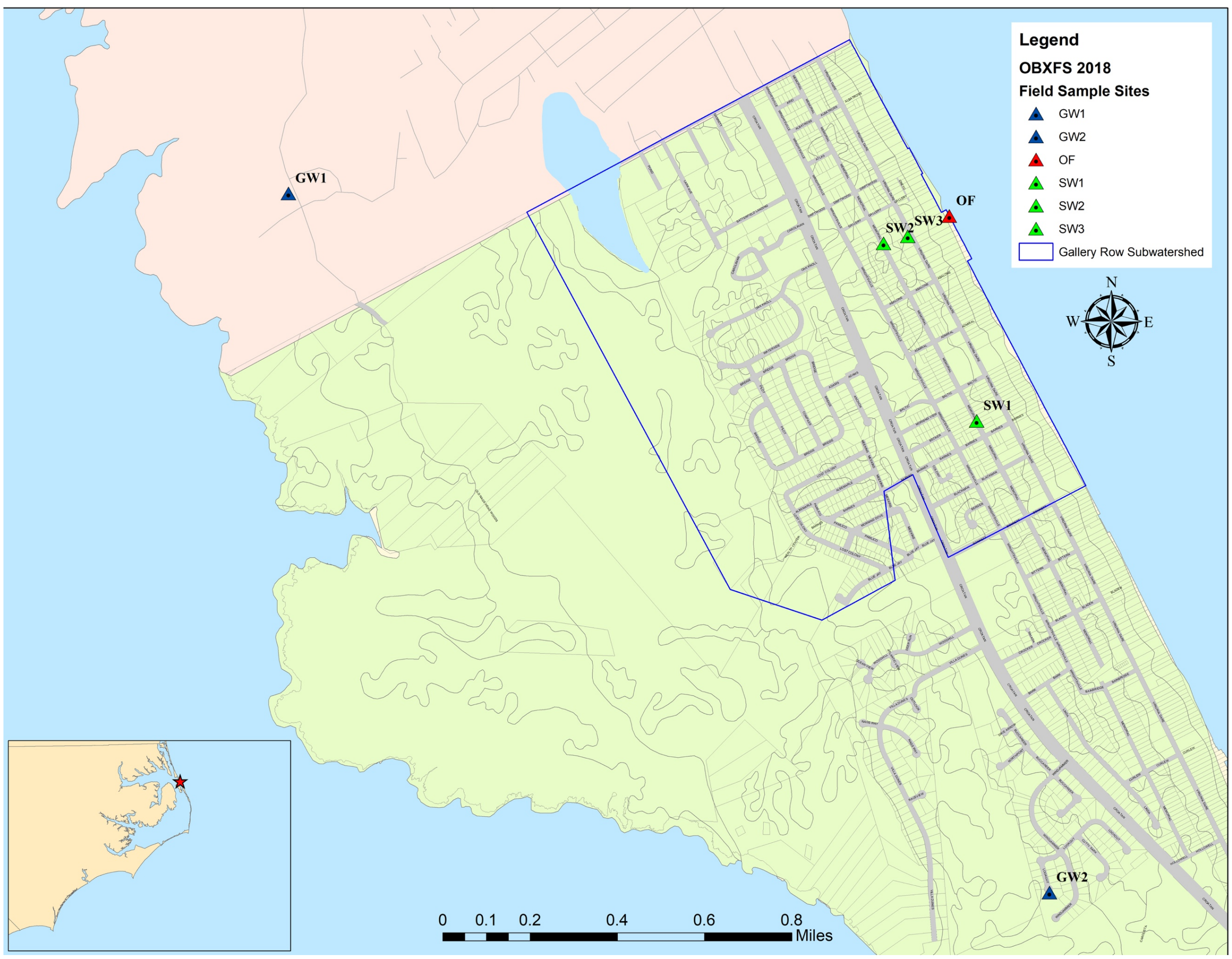

Figure 5: OBXFS Field sampling sites and Gallery Row sub-watershed in north Nags Head, North Carolina. Map sub-watershed, town limits, and road data provided by the Town of Nags Head.

Table 1: Names, abbreviations, and geographic coordinates of sampling locations for the field-based water quality research component of the 2018 OBXFS Capstone research project.

Sampling site name	Abbreviation	Geographic coordinates
Groundwater 1	GW1	35.99035° N 075.66731° W
Groundwater 2	GW2	35.96626° N 075.63715° W
Surface-water 1	SW1	35.98202° N 075.63947° W
Surface-water 2	SW2	35.98802° N 075.64304° W
Surface-water 3	SW3	35.98823° N 075.64204° W
Outfall	OF	35.98886° N 075.64031° W

Human Dimensions

We conducted semi-structured qualitative interviews based on a set of open-ended questions, provided in Appendix A. The interviews targeted four main topic areas, but by virtue of asking open-ended questions, allowed participants the latitude to address other topics that were important to them. We asked participants to describe their history in Nags Head, their connections to water reservoirs, and the relationship between the town and water. Interview questions aimed to identify any changes in water quality and quantity that participants had noticed and to discuss details about experiences with flooding, other storm events, and flood prevention measures. Interviews also covered wastewater treatment, including questions about septic tank system maintenance, centralized wastewater treatment, and the Town of Nags Head's efforts to manage wastewater. Finally, we asked participants about their perceptions concerning relative responsibilities for water quality and quantity and the adaptability of the town to changing conditions.

We interviewed residents and business owners of the Gallery Row sub-watershed in Nags Head, as well as some additional residents, whose properties are located outside this sub-watershed. We contacted potential participants by canvassing local businesses within the sub-watershed and through recommendations and referrals from field site professors, Outer Banks Field Site (OBXFS) Community Advisory Board (CAB) members, internship mentors, and Coastal Studies Institute (CSI) employees. After these initial contacts were made, we employed a snowball method to expand our pool of participants. The snowball method involved requesting additional participant referrals upon the completion of each interview, creating a chain effect of participant referrals. Interviews occurred between October 5, 2018, and November 14, 2018, and ranged from 20 to 80 minutes in length.

We conducted a total of 27 interviews. Three of these involved two participants, but for the purposes of our study are counted as one. Twenty participants were property owners within Gallery Row sub-watershed and seven were outside Gallery Row sub-watershed. Participants were also characterized by length of residence in the Outer Banks: six participants were lifelong residents, denoted as "born and raised;" fifteen participants were considered "long-time" residents, those who have been living in the Outer Banks for ten or more years; and six participants were considered "new arrivals," those who have lived in the Outer Banks for less than ten years.

All interviews were audio recorded with the participants' consent. Recordings were then transcribed verbatim. Transcripts were coded using NVivo v.11, a text analysis software program. Two students coded each interview, creating "codes" or labels to categorize each interview's contents. By reviewing the contents of these "codes," we identified patterns in the data and organized these to describe emergent themes related to our interview topics. Our interview and analysis methods produced rich qualitative data, but we recognize that our findings cannot be generalized to all residents of the Town of Nags Head or the Outer Banks. All interviews and analyses were conducted to maintain the confidentiality of our participants' identities.

Historical Water Level Study

Data source and explanation

Historical data from groundwater and surface-water reservoirs in Nags Head were collected by Environmental Professionals Inc. consulting firm at the request of the Town of Nags Head. The chemical and biological analysis of water samples was completed by Envirochem Laboratories in Wilmington, NC. The data were provided as Microsoft Excel sheets that included information for 23 locations (Figure 6) sampled for 13 water quality parameters from March 2011 to June 2017. We only used data from groundwater wells in our historical water level study and a single surface-water sampling station, Wrightsville #2, in our field-based water quality study. The water quality parameters reported include: depth to groundwater (DTGW; in.), field temperature (^{o}C), dissolved oxygen (mg/L), specific conductance (μmhos/cm), salinity (parts per thousand; ppt), pH, turbidity (Nephelometric Turbidity Unit; NTU), ammonia nitrogen (mg/L), total phosphorous (mg/L), nitrate nitrogen (mg/L), nitrite nitrogen (mg/L), fecal coliform or *Escherichia coli (E. coli*; Col/100 mL), and *Enterococci* (Col/100 mL).

There were eight groundwater monitoring wells: Blackman, Curlew, Juncos #1, Juncos #2, Nags Head Control Site, Nags Head Fire Station, Old Cove #1, and Old Cove #2 (Figure 6). The Blackman groundwater monitoring well was only sampled for two years and two months- from March 2011 to May 2013 - out of the six years and three months - March 2011 to June 2017- total. The other seven sites were sampled through June 2017. Additionally, data available for the years 2011 to 2012 only provided DTGW data and fecal coliform measurements for each of the eight monitoring wells. Reports of fecal coliform and *E. coli* were inconsistent throughout the monitoring years. Groundwater data were not reported for December, January, and February of any year, with exception of February 2014.

Historical precipitation data were obtained from the First Flight Station weather monitoring site using Weather Underground's official online database (Monthly History, 2018). We used monthly precipitation sums from October 2010 through September 2017 and organized the data into water years starting with 2011 and ending with 2017, each water year running from October 1 until September 30 of the following calendar year.

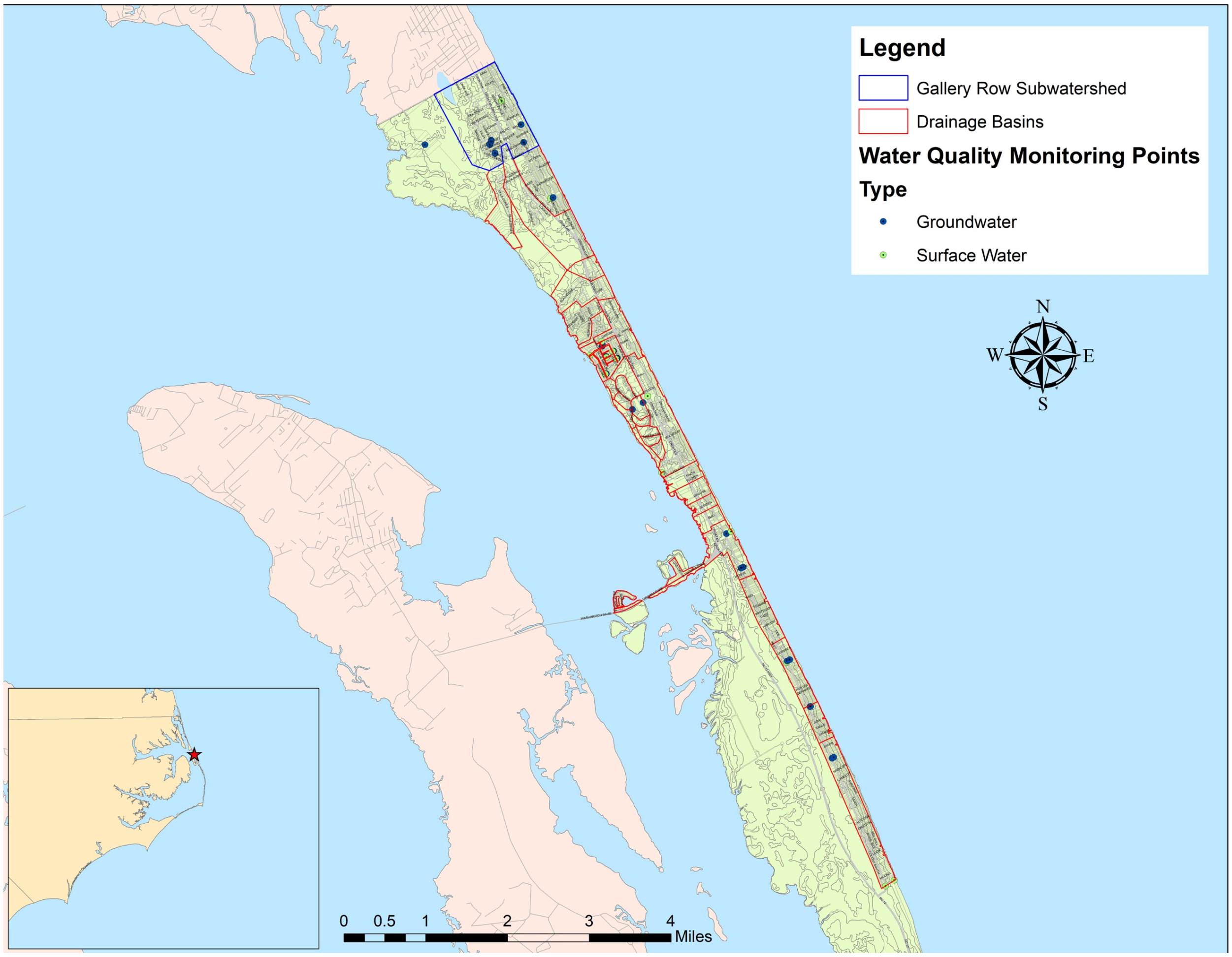

Figure 6: Historical groundwater and surface-water sampling locations used by the Town of Nags Head's water quality study in Nags Head, North Carolina. Map sub-watershed, town limits, road, and historical water level study location data provided by the Town of Nags Head.

Data analysis and calculations

To determine whether water level has changed in a consistent pattern across the landscape of Nags Head, we compared elevation and mean DTGW. Elevation data were gathered from NC One Map, a digital elevation model (DEM) with contour lines from ArcGIS (NC One Map 2018). To compare mean annual depth of groundwater to the median depth of groundwater for the years 2011 to 2017, we calculated the median DTGW for each groundwater well across all sampling dates and the geometric mean of the groundwater data for each water year at each well. We chose median DTGW to represent the baseline depth in order reduce the influence of extreme precipitation events and subtracted baseline DTGW from mean DTGW of each well for each water year to obtain the mean difference from baseline DTGW, which served as a measure of annual variability in DTGW. Furthermore, mean annual DTGW data from each well were organized by elevation to analyze the effect of elevation on mean DTGW. Monthly precipitation data from the First Flight weather station were summed by water year. We chose to consider all data points for each sampling date even if a majority of the other wells were not sampled to include more data points for each well and to better inform how water level has changed over time.

Spatially, we categorized the eight groundwater wells into six drainage basins based on location (Table 2). These drainage basin classifications were obtained from the Town of Nags Head as a geospatial ArcView data layer. From here on, the terms drainage basins and sub-watershed will be used interchangeably. Monthly groundwater level data for each drainage basin were categorized by season, classifying winter months as December to February, spring as March to May, summer as June to August, and fall as September to November. For these seasonal calculations, sampling events were only included in calculations if data for at least four of the groundwater wells were recorded during one sampling event. This was done in order to more accurately assess the overall changes in water level over time and space in Nags Head. We calculated the mean DTGW for each drainage basin by water year for all of the respective wells' data. We examined seasonal data within drainage basins that reflect the influence of topography and landscape features, such as Highway 158, on water movement within the landscape, and compared locations on the more developed east side of the highway to those on the less developed west side.

Table 2: Nags Head historical data groundwater well categorization into drainage basins and corresponding elevation for each well.

Drainage Basin	1	2	Not listed	8	16	32
Wells included	Blackman	Curlew	Nags Head Control	Old Coves 1 & 2	Nags Head Fire Station	Juncos 1 & 2
Elevation (feet)	8	6-8	28-30	4	12-14	2-6
East or West of Highway	East	East	West	West	West	East

When analyzing the long-term patterns of groundwater level, we chose to organize the DTGW measurements taken from each well by water year and calculate the mean DTGW from the entire dataset of DTGW measurements. We chose to use mean DTGW as the baseline in this calculation to account for extreme precipitation. We applied a linear regression model to determine mean changes in DTGW over the seven-year dataset.

To examine if historical data collection included the range of precipitation amounts experienced by our study site, we compared patterns in precipitation and the number of historical data sampling events using a linear correlation coefficient analysis. We compared historical precipitation data to sampling event dates to determine the relationship between amount of precipitation and sampling frequency. Lastly, we analyzed sampling across each season.

Water quality field study

Sample collection

The qualitative aspects of this project included visual and olfactory observations of the water quality at each of our six sampling sites, although the bulk of the analysis is quantitative in nature. At each site, we collected a one-liter water sample in a sterile, acid-washed high-density polyethylene (HDPE) bottle for nutrient and bacteria analyses, and a four-liter water sample in a glass bottle for caffeine analysis. At each of the six locations, we also used a Yellow Stone Instrument (YSI) water quality monitoring device to measure water quality parameters, including temperature, salinity, conductivity, and dissolved oxygen. At the two groundwater sampling sites, we used a depth-to-groundwater meter to record the depth of each well. We collected three baseline samples approximately two weeks apart: October 5; October 10; and October 24. The sites were sampled twice during a storm event on October 25 and October 26. For the purposes of our study, a storm event was defined as any visible precipitation within our study site. Samples for caffeine analysis were collected on the last three sampling dates. For each collection event, we sampled as close to low tide as possible. Upon collection, samples were immediately placed out of direct sunlight in a closed cooler with ice. We kept all samples in coolers until we returned to the lab, where we immediately processed bacteria samples, filtered nutrient and caffeine samples, acidified and refrigerated caffeine at 10^{o} Celsius, and froze nutrient samples at 0^{o} Celsius. A full sampling protocol is provided in Appendix B.

Hydrology Processing and Analysis

Bacteria

We processed and analyzed water samples for total coliforms and concentrations of *Enterococcus* and *E. coli* bacteria using IDEXX Laboratories Enterolert and IDEXX Laboratories Colilert protocols and materials, respectively. We used an aseptic technique to reduce contamination and prepared two sample bottles for each water sample: one for the Colilert test and one for the Enterolert test. We diluted our water samples by one order of magnitude with sterile, deionized water (10 mL of sample in 90 mL of water) and adjusted calculations accordingly. The contents of the test kit packs were added to the vessels after the sterile water and inverted. We then added 10 mL of sample to each vessel, which was inverted again. The solution mixture was poured into a Quanti-Tray 2000, containing 49 individual wells, using an IDEXX Quanti-Tray Sealer. Once we sealed each tray, we placed it in a 41^{o} Celsius incubator for Enterolert samples or a 35^{o} Celsius incubator for Colilert samples. We incubated the trays for 24 hours and read the results using the IDEXX Result Interpretation table to obtain a Most Probable Number (MPN) for each bacterial group.

The IDEXX Colilert Test uses a proprietary technology called Defined Substrate Technology (DST) that counts for total coliforms and *E. coli* bacteria. There are two nutrient indicators in the test that are metabolized by enzymes in coliform and *E. coli*. When these coliforms are present in the test, the solution turns from colorless to yellow. We used this yellow color to interpret results using a Result Interpretation table from the IDEXX manuals and resources. According to the manual, cells that appeared yellow were counted as positive for total coliforms, while cells that fluoresced were positive for *E. coli* (IDEXX US).

The IDEXX Enterolert Test also uses proprietary DST nutrient indicator technology to detect *Enterococci*; when metabolized, the indicator fluoresces. We read results using the Result Interpretation Table, which indicated that a lack of fluorescence was a negative result for *Enterococci*, while cells that exhibited blue fluorescence were a positive result for *Enterococci* (IDEXX US). We determined fluorescence for both tests using an ultraviolet light, which we held approximately five inches away from the sample tray. We then counted and interpreted positive cells by obtaining a MPN from the IDEXX Quanti-Tray/2000 MPN table. The MPN determined the bacteria colony count, which we then compared to environmental health standards. A full bacteria sample processing and analysis protocol are provided in Appendix C.

Nutrients

We utilized a filtration manifold consisting of a small glass box, tubing connecting filters, and a vacuum pump to filter nutrient samples, collecting filtrate in falcon bottles. We placed pre-combusted Whatman GF/F filters between the manifold and each filtration tower. Prior to filtration, we rinsed the manifold components and falcon tubes with the sample, and individual samples were inverted. We poured at least 30 mL of each sample into the corresponding filtration tower. After filtering at least 30 mL of each sample using the vacuum pump, we removed, capped, and labeled each falcon tube, and then transferred it to a freezer to await analysis.

We analyzed samples within 30 days of collection with a Lachat Quickchem with automated flow injection colorimetry. The Lachat Quickchem utilized the Cu-Cd reduction method for nitrate-nitrogen (NO_{3-} -N) analysis; phenol hypochlorite for ammonium-nitrogen (NH_{4+}-N) analysis, and antimony-phosphomolybdate complexation for orthophosphate, (PO_4 –P) analysis (according to Parsons et al., 1984).

Caffeine

For caffeine analysis, we filtered all four liters of sample for each location according to the nutrient sample filtration method, using a manifold and vacuum sealed pump with filtration towers and Whatman GF/F filters. We acidified each sample's filtrate with diluted hydrochloric acid to a pH of 4-5 and refrigerated them at 10° Celsius until extraction.

We concentrated surface-water and groundwater caffeine samples using filtration through ethyl acetate-washed Oasis HLB cartridges within 30 days of collection. We extracted samples and analyzed them with the standard operating procedure for isolation of PPCP's in surface-water or groundwater, according to Analytica Chemica Acta (Zhang et al., 2006). Due to time and equipment restrictions, we were not able to run all four liters for all samples, but instead processed between 2250 mL and 3525 mL of each sample. Dr. Sid Mitra (ECU) analyzed extracted samples on a gas chromatograph mass spectrometer (GCMS; Shimadzu). He based concentrations on a calibration curve constructed using samples with known caffeine concentrations.

Data analysis and calculations

For each parameter, including all nutrient and bacteria data, we calculated mean concentrations and standard deviations for each surface-water (SW), groundwater (GW), and the outfall site across all baseline sampling events and again across both storm sampling events to compare variation between individual sampling locations. We also calculated mean aggregate concentrations for all surface-water (SW) sites for all baseline sampling events, all SW sites for all storm sampling events, and both groundwater (GW) sites for every sampling event. We used these calculations to compare aggregate bacteria and nutrient concentrations at SW sites under storm conditions to SW sites under baseline conditions and to the control GW sites. To analyze our caffeine data for presence at individual sampling locations and differences between baseline and storm samples, we compared the individual concentrations of each site for each sampling event. For bacteria analysis, we removed the storm values to look at only the baseline conditions and compared these to EPA thresholds for recreational waters to demonstrate bacteria pollution in surface-waters under baseline conditions. In order to contextualize our nutrient data within the larger historical dataset, we chose to compare nitrate-nitrogen concentrations from our field data collection to years 2013 through 2017 of historical data at the Wrightsville #2 surface-water sampling site because it was the closest surface-water sampling site to our field sampling locations. To make this comparison, we used Excel to create a box plot using the maximum, minimum, median, and upper and lower quartiles to illustrate the variability of the data. We then compared the average of our field sampling nitrogen concentrations from each of our three surface-water locations over all five sampling events to the range of historical values.

Results and Discussion

Participants' Environmental Observations and Perspectives on Wastewater Treatment in Nags Head

Septic leachate and rising groundwater tables could pose a threat to public health in coastal communities like Nags Head. Previous studies have shown that many homeowners do not realize the important links between maintaining a properly functioning septic tank system, good water quality, and health (Fizer et al., 2016). Our interviews with local property owners revealed four major themes relating to individuals' perceptions of wastewater management and observations of their environment in Nags Head. These include: sense of place and water identity; evidence and drivers of water quality and quantity; perceptions of septic risk and barriers to change; and responsibility.

Our findings on perceptions of wastewater reflect our participants' personal experiences with their properties and focus on their observations of water quality and quantity in Nags Head. We found a diversity of opinions on water quality and quantity and widely varying environmental observations among participants, who noted that storms, increases in flooding, and erosion were all present in Nags Head. As in Brownie et al. (2015), we found a general lack of information regarding Nags Head's wastewater treatment systems and current management practices. Our discussion of wastewater knowledge and environmental observations centers on participants' attachments to place, views on development, and beliefs about responsibility for managing water quality and quantity and adapting to change in Nags Head.

Attachments to Place and Water

Sense of Place and Water Identity

Participants described strong attachments to the waters of Nags Head and expressed appreciation for the quality of life available to them in the town. Many participants described revolving their entire lives around visiting and appreciating the ocean. They attributed this high quality of life to the waters around them, and in tandem, to the development of what we refer to as their "water identity." A participant's 'water identity' encompasses one's connection to, use, and appreciation of water and is influenced by one's sense of self and belonging. Water identity can be considered a kind of place attachment wherein a place is symbolic of one's own definition of oneself or a reflection of the kind of person one is. Place attachment can be a factor in how individuals or communities recognize change and respond to it. Changes that disrupt those attachments can lead to engagement in stewardship, other place-protection activities, or place-adaptation measures. Participants' place attachments could motivate current and future decision-making regarding wastewater management in the face of environmental changes.

Numerous participants also ascribed much of their place attachment or sense of place to history, memories, familiarity, lifestyle, and routine. This most often occurred with residents who were born in the Outer Banks and/or had lived here essentially their whole lives, but these sentiments were expressed to some extent among all of our interview participants.

A few participants expressed a spiritual connection between their sense of self and Nags Head's waters. This form of place attachment or aspect of water identity represented how waters influenced and guided their lives.

"Everything, I mean it really is for me. Some people have religion and certain other things, but the ocean is what keeps me grounded. It's what keeps me connected. It's almost spiritual in a way."

As this participant expressed, the bodies of water in Nags Head are more than a physical resource, and played an important role in their overall well-being.

Many participants expressed attachment to Nags Head because of their recreational use of the area. Recreational uses varied widely among participants, but all revolved around water. Our participants would often default to speaking of their favorite coastal recreational activities in our interviews. Several participants went into detail as to the value of this area because of their favorite recreational activities. One of the key benefits of recreating in and around the waters of Nags Head for many participants was the social aspects of recreation. These participants saw recreational activities as a way to connect with the town, their neighbors, and the natural environment. Further, many attributed recreational activities at the coast with a happier, healthier lifestyle. This lifestyle is one that is reliant on our participants' setting, so it is interconnected to each participant's sense of place.

Community, Livelihood, and Tourism

Connecting with neighbors through recreation was one of the keys to the strong sense of community that was apparent in many of the interviews. This manifested in multiple ways, such as an appreciation for a community of people with similar values regarding sense of place and water identity. One participant expressed their sense of community directly relating to the bodies of water surrounding them in Nags Head.

"They're extremely important to me. That's what makes this community the way it is. It's unique, it's special, and without having both of those… we have amazing ecosystems on both sides, and they make our community what it is."

As this participant describes, the ocean and sound hold the Nags Head community together, and without them, the community would not be what it is today.

In addition to the water, the rich history of Nags Head, including fishing, other forms of recreation, and aspects of livelihood contributed to the sense of pride in their coastal community that many participants expressed. Multiple participants expressed a deep appreciation for the support network which they perceived the Nags Head community offers. This attitude among several participants was centered around appreciation for others; one participant specifically noted that the community aids one another during hard times as well.

"But when I see these businesses flood, and I see my neighbors flood, it's just disheartening. It's not a matter of me saying 'oh hoo,' you know 'we're fine.' I'm in the fight."

For numerous participants, the detrimental impacts of flooding and other hardships with water were noticed and felt throughout the community, even if their property did not personally experience such impacts at the same time. This collaborative awareness and care throughout the community resonated in these responses and revealed a collective resilience.

Many participants expressed a sense of pride when they described how their jobs were reliant on the beach because it allowed them to live on the coast. Many of these same jobs were also intimately related to tourism in this area. Because the Nags Head's economy is largely tourism-based, and, therefore, tourism is such a sweeping part of living in Nags Head, it heavily contributed to our participants' senses of place. As some participants asserted, the area would not be the same without these tourists. Some went even further, explaining how the town works diligently to maintain the tourism industry in Nags Head.

> *"Without the beach, we wouldn't have the tourists, and that really is everything, I think to bring in people to the beach is really the livelihood of the whole town because they keep taxes down. They mean everything. It would be a pretty desolate area if we didn't have a beach that people knew to come to."*

This reliance on tourism and subsequent reliance on the waters around Nags Head further developed participants' senses of place, as well as those of the community and town. The inter-dynamics of livelihoods, tourism, and functioning of the town were yet another layer to the water identity landscape.

Many acknowledged how the health of the waters influenced the vitality of the town in terms of livelihood and tourism. They expressed not only wonder and appreciation for the environment, but also the intertwined importance of environmental quality for the sustainability and quality of life of coastal communities around the world. Multiple participants said they felt this was integral to the safety and success of coastal areas. One participant explained,

> *"The tourism industry is driven by the beach, so it's essential that we take steps to protect our ocean and to protect our beaches to make sure that we can continue with that uninterrupted revenue stream. Maybe a little more globally, a lot more globally, we need to keep the ocean clean, not only here locally but throughout the world to make sure that all of the populations of wildlife that use the ocean remain robust."*

This appreciation for waters expanded to passion for the environment for several of our participants. They recognized that the waters they loved and depended on are impacted by a multitude of factors in the environment, not only in their immediate coastal environment, but for coastal environments and communities around the world.

Change and Resilience

Our interview participants expressed a resounding sense of pride in the perceived resilience of the community in the face of constant change and associated stressors. Many participants directly identified with this resilience in their own lives, describing change and resilience as part of the character or culture of the Outer Banks.

> *"I think people really feel an innate connection to the ocean, and it's something that you really don't know what you're missing until you have it there... But I think it certainly is embedded in quite a few of the community members here, and it's almost essential that they live near the water, despite some of the hazards that it promotes."*

Throughout our interviews, many of our participants, like the one quoted above, indicated that the hazards associated with living by the water, such as flooding, were well understood among residents as a normal part of life here; a package deal. Participants commented on how flooding is a part of living in Nags Head, and how adaptation to flooding was more favorable than simply moving to a place with less risk. For them, and especially for participants who have been living here a long time, their sense of place and water identity linked directly to the dynamic coastal waters and environment, as expressed through strenuous experiences, recovery, and adaptation. Much of the community in Nags Head and the Outer Banks has learned ways to become more resilient and essentially 'ride the waves' in order to continue living near the waters they love and respect.

> *"It's amazing, the power of water. I never would've known had I not lived here that water can pick up things and move it. It's like, 'How did that happen?' But I've actually seen it, it's strong."*

Participants like this one choose to establish their lives on the Outer Banks, despite the catalogue of imminent risks, such as flooding, that inhibit a typically 'stable' lifestyle in part because of their appreciation for water in and of itself.

For almost all of our participants, we found that their sense of resilience was embedded in the sentiment that they considered the Outer Banks to be their home. Since their homes inherently required adapting to changing conditions, there seemed to be a widespread understanding that adaptations were part of the deal if they wanted to stay. Indeed, many participants had discovered that as their experiences living on the Outer Banks accumulated over time, they became more aware of the dangers associated with changing conditions. This awareness grew through observation, major experiences, or shared common knowledge that they would sometimes try to impress upon tourists and others with less information. Many participants' cautionary tales would often, to their frustration, fall on deaf ears when addressed to people more focused on their vacation. For many of our participants, their awareness and sense of urgency for hazards related to wastewater management and stormwater was driven in direct correlation with a major recent wake-up call of their own: Hurricane Matthew. This storm reinforced the extent of the destructive impacts a major storm could leave in its wake and invigorated them to pay more attention and seek out information regarding adaptations they could implement.

These connections to the Nags Head area have strong implications for the motives and driving factors surrounding managing, preserving, and restoring the natural environment of Nags Head. Participants' understanding of Nags Head's dynamic coastal environment shone through during our interviews, and ultimately gave us a better sense of their values relating to the changing environmental conditions and decision-making. The influences on their values were evident by the overlap between a strong sense of community and resilience to changing coastal conditions.

Evidence and Drivers of Water Quality and Quantity

Participants' strong connections to water and the important roles that water plays in their senses of community and livelihoods indicated a keen place attachment to Nags Head. Their place attachments and water identities likely contributed to participants' recognition of the vulnerability of the area and concerns about Nags Heads water quality and quantity. They discussed changes related to water and the environment that they have been observing over the years and the potential drivers of those changes as well.

Our participants noted water quality in a plethora of contexts. If they referenced water quality in a good context, participants said they generally felt as though the ocean and sound were clean, and did not express any concerns. If participants referenced water quality in a bad context, they expressed hesitation regarding the cleanliness of the water, concerns of the interaction of septic tanks with the groundwater table, or trash in the water. Although participants had different opinions on the drivers of this quality, all acknowledged that Nags Head's water quality is essential to the town's prosperity and well-being.

Many of the participants who believed that Nags Head's ocean waters were clean and healthy also acknowledged that they were uninformed of water issues within the area. Despite being uninformed, some of these participants concluded that Nags Head's waters were good by drawing comparisons to the ocean waters in other beach towns along the East Coast, such as Virginia Beach and New Jersey. The main perceived impairment of good water quality was trash pollution carried by wind from the beaches or inland to the water. However, this concern was viewed as unsubstantial due to the frequent community-organized beach clean-ups, where trash and plastics from littering were removed. Some participants also believed that the cleanliness of the waters varied seasonally. One participant found that because "there's more people in the summer. There's more waste. There's more everything during the summer." This participant suggests that there may be a notable difference between the amount of trash produced during the summer and the winter months and the health of the ocean waters in the summer months compared to the winter months because of the stark differences in number of tourists vacationing between the two seasons.

Bad quality of water was discussed in interviews almost three times as much as much as good water quality. Nearly all participants said that they observed bad water quality in Nags Head, even if some of these participants had previously mentioned good water quality or a lack of environmental concern. Participants attributed the bad quality of water to various sources and causes. The most commonly referenced concerns regarding water quality were animal waste, trash, pathogens, and bacteria, whereas the most commonly mentioned contributors to poor water quality were runoff from land in town and inland areas, septic tank systems, and outfall pipes.

Discussions of poor water quality touched on the sound, ocean, drainage ditches, and groundwater. Moreover, both biological and physical factors were cited as evidence for these perceptions of poor quality, including dead animals, particularly birds and fish, and warning flags in addition to the presence of litter. Participants described how storms, especially heavy rainstorms, and development particularly of rental homes, aggravated water quality. They suspected that septic tank failures and poor maintenance leached septic effluent into groundwater or runoff, which eventually went into drainage ditches, the ocean, and the sound. Nearly all participants were concerned that rising water table levels were enhancing septic leachate contamination of the groundwater. These concerns translated to participants expressing fear for a variety of illnesses, including cancer, cholera, hepatitis, ear infections, and rashes.

> *"I think poorly functioning septic systems that discharge untreated waste into the water table, that's a concern of mine. If there ever exists an occasion where septic products or septic effluent makes it into open ditches and things or runs into the waterways, I'd have a big problem with that as well. I'm sure that it happens and*

we have a monitoring system but testing, regular testing that goes on, that's a big concern for me."

This participant expressed concerns regarding the interaction of untreated septic waste with the groundwater table. They make note that they are sure it happens, but suggest testing to ensure that the septic leachate is not harming Nags Head waterways.

An interesting distinction was found in the discussion of the sound and ocean's water quality. The sound waters were only referenced a total of five times from three participants. Two of the three participants only referenced sound waters to compare its health to that of the ocean, perceiving the sound as dirtier. The reasoning of participants was that sound waters are historically more stagnant due to inlet dynamics, which have limited sound and ocean interaction.

Evidence of Water Quantity

Although participants were not specifically asked about their observations of water quantity in Nags Head, there were five cases in which participants commented on the high groundwater table. These cases were distinct from other mentions of water quantity in that they were not attributed to increased storms, flooding, or development. One example of a participant who noted the high groundwater table impacting water quality stated,

"You've got a groundwater table is embarrassingly high. We have water infiltration due to groundwater, tide raising, water levels, etc., etc., etc. So water quality is a huge thing, and when you're in and around the beach in summer when there's a water quality advisory or alert, it's a huge thing."

This participant expressed concerns not only towards a high groundwater table, but also regarding water quality. We found that participant's observations of water quantity came largely from factors that were visibly accessible to them. For example, participants frequently commented on increased flooding, which may be seen either on their property or in surrounding areas, as opposed to commenting on the groundwater table which may not be directly observed.

Flooding and Storms

Observations of increased frequency of storms and flooding and their roles as drivers of changes in water quality and quantity were common across the majority of participants. Many personally experienced the impacts of flooding. According to our participants, flooding may occur due to large storms like hurricanes or as a result of smaller rainfall events, but flooding impacts largely depend on location as opposed to amount. Certain participants only mentioned large hurricanes as being impactful where they live, whereas other participants stated even small rain events cause flooding and standing water on their property. One rain event frequently mentioned was the July 2018 rain. This event was mentioned almost as frequently as Hurricane Matthew, and it was described as bringing as much rain as a hurricane, but it was Hurricane Matthew that brought a new sense of fear to participants as they noted flooding in places that had never flooded previously.

"When we started here before Matthew, this area was fine, and if you talked to the old-time residents, they would tell you they have never flooded… inside the

house, and some of them have lived here since the eighties, they would say the streets have never flooded like this, houses have never flooded."

As this participant describes, Hurricane Matthew flooded areas of Nags Head that had never before flooded. Participants cited flooding as a reason for poor water quality and increased water quantity due to standing water and problems with the outfall or drainage. Many stated there is only so much they can do as an individual in order to combat flooding without spending large sums of money. Most participants had a general acceptance of flooding, realizing that it is a way of life and it's something they must accept as a result of living on the coast.

"I think it's just like a way of life. You kind of accept that flooding is going to happen if you live near water."

Participants like this one realized that flooding in Nags Head is a normal part of their life. Even participants that stated they had no prior knowledge of flooding before moving to the area accepted flooding as a part of living in this place.

<u>Development</u>

Participants expressed concern that development and associated removals of trees, vegetation, and permeable soils was driving changes in water quality and quantity in Nags Head. They blamed this development for increasing the amount of impervious surfaces, which prevents water from infiltrating the soil. This may be harmful to water quality as instead of being filtered by the soil, the standing water runs to a ditch or outfall and may carry oil, trash, nutrients, bacteria, and other particles along with it.

"You cannot pave more of this island and think that it is not going to geometrically increase the flooding issue. And not just here, but you're going to start to see flooding in areas other than this that had never flooded before."

As this participant recognized, impervious surfaces worsen flooding issues not only in places that have previously experienced flooding, but in newly developed areas as well. One participant noted the water quality was "much worse given the amount of development that's happening now." More specifically, participants noted newer, larger ocean-front homes on septic tanks as a main concern. They described how four ocean-front homes might be built on a lot that originally only held one. This increase in the number of homes and quantity of humans on the same land area was associated with a perceived notion of bad water quality.

"Now you can look across the street and see that we now have 14- or 15- or even 16-bedroom houses on small pieces of property that are strictly on septic down there. That's had a big impact on the beach and the sound as far as water quality."

This participant observed the large ocean-front homes being built on small lots and acknowledged that their septic tanks impact water quality in both the ocean and sound.

In their discussions of development, participants commonly mentioned the Town of Nags Head and developers. Half of participants mentioned the Town in relation to development, but perceptions varied: many believed the Town was proactive and strict in their building regulations, whereas some believed the Town needed to "revamp their planning." Another participant wanted Nags Head to "stop building, stop permitting, stop over-permitting for spaces that don't already exist." These differing viewpoints represent a point of disconnect between participants and the Town's regulations and planning. In addition to the Town, a handful of participants attributed development to the developers themselves.

> *"The builders and the developers are the ones that always come out on top, and the people that are suffering are the people that live here."*

Participants like this one noted that developers will not change and that they benefit from more construction, while the local residents suffer the consequences of increased flooding and a perceived worsening of water quality.

Although development was a concern to many of the participants, citing it as a reason for the increases in flooding and worsening of water quality, some viewed it as a necessity to life on the Outer Banks. The tourism industry in the Outer Banks is vital to some participants since it allows them to live comfortably in a resort town. Despite its important role in supporting tourism, one participant questioned if enough is being done in order to combat the negative aspects of development as well.

> *"So, it's a battle between wanting a big house there because tax revenue. And that puts poor people in business: cleaning, plumbers, etc. So I know all the positives, but are we really dealing enough with the negatives?"*

This hypothetical question brings up an interesting battle between participants wanting more tax revenue from building more houses and questioning if enough is being done to address the perceived issues of development. This presents a difficult situation. Denser development and associated economic growth mean citizens can make an income and live in Nags Head year-round, but at the same time, more development may be contributing to an increase in flooding and a worsening of water quality.

> *"I think as the Outer Banks grows and tourism continues to increase, we're going to keep seeing more demand for denser development, and that has an impact on wastewater, what we can put in the ground to accept wastewater from all of the added infrastructure that comes with developing tourism economy."*

As this participant describes, with tourism driving denser development, there must be some alternative method to dealing with wastewater. In other words, as growth of the tourism industry continues in Nags Head, there must be some sort of adaptation taking place in order to combat the increase in wastewater from more development.

Climate Change

Even though we left the term 'climate change' out of all interview questions, some participants cited climate change as a reason for their environmental observations. They suggested that climate change was altering weather patterns, including increasing the frequency of storms. One participant reported,

> *"Climate change is happening. Because of the change in the climate it's altering our weather patterns and we've seen more frequent tropical storms and hurricanes, more frequent Nor'easters in the winter, which increase wind energy so there's larger wind storms causing larger ocean waves and creating more erosion on both the sound side and the ocean side."*

This participant connects shifting climate patterns with increased storm erosion. Those shifts can also contribute to flooding and bad water quality for Nags Head in combination with increased development and impervious surfaces.

Other participants mentioned 'global warming' or 'sea-level rise.' Those who mentioned global warming noted worsening erosion and a decrease in the size of the beaches. Beach nourishment was mentioned by a few participants who said it alleviated the impacts of erosion, but were unsure why erosion was worsening in the first place. Sea-level rise was mentioned as a reason for decreased groundwater quality, stormwater flooding problems, and sewage issues.

> *"Climate change and the weather patterns have impacted stormwater flooding problems along with sea-level rise, our water table, and the subsurface-water table increasing, so that, in turn, is creating issues for our groundwater. It then makes it more challenging with our septic systems and drain fields. They're not functioning appropriately and may be contributing more bacteria into our groundwater"*

This participant attributed climate change to impacting sea-level rise, which in turn is decreasing the depth of groundwater from the surface. The rising water table enables septic leachate to interact with groundwater, which can cause decreased quality of water, public health concerns, and septic system failure.

Perceptions of Septic Risk and Barriers to Change

Our participants had varying levels of knowledge regarding wastewater treatment in Nags Head, but almost all of them shared similar sentiments, especially when it came to financial and water quality issues associated with septic systems. While many participants were relatively uninformed about how exactly their septic tanks worked, nearly all of them knew that their property is on a septic tank system. There was a dominating opinion that septic tanks pose a risk to the water quality of the area, but our participants had a difficult time pinpointing the factors contributing to that risk. A large number of them talked about their lack of knowledge regarding septic systems' influences on the hydrological cycle. One of our participants explained it this way:

> *"In general, I think people buy a house, and depending on how much education they get from their realtor, from their building inspector, they probably don't know too much about it, and it's sort of an out of sight, out of mind type thing."*

For this participant and others, it seemed as though the lack of knowledge about septic tank systems and their potential impact on local hydrology was due in part to the fact that homeowners do not see the actual septic system on their property much, if at all. Another participant mentioned, "most people don't understand the septic tank processes and don't understand that it relates to our groundwater and eventually goes back into our water cycle."

Risk from Septic Systems

The majority of our participants had limited information about septic tank systems, but, despite this, expressed more negative responses about septic systems than positive responses. Most assumed they must be contributing to poor water quality, and a few participants even discussed septic's negative influence on water quality before being asked about it directly. Many participants believed the frequent beach closures and illnesses were linked to water quality problems caused by septic tank leachate. They described how it was a major problem in Nags Head that septic tanks were failing "left and right" and brought up how several residents have had to get their tanks completely replaced or switch to above ground tanks. They also discussed how above ground septic tanks are unsightly in a town where aesthetics is so highly valued.

While there were a number of issues that people had with septic systems, the biggest problem for most people was standing water during major rain events. Participants complained about septic water overflow occurring during storms such as Hurricane Matthew. One participant discussed how they were much more cautious during the storms due to perceived contamination from septic tanks:

> *"The water that was standing outside, oh my God, it was nasty to me. Like I said, I'm much more aware about this stuff than I used to be. I wouldn't go out there without boots."*

This quote was representative of a sentiment that many participants shared, that septic tanks were a large contributor to water contamination. They believed that this was worsened during major rain events, as water from septic tanks interacted with the standing stormwater, and this was a concern for many of our participants.

While it was recognized that it is mostly an individual responsibility to maintain one's septic system, the participants also discussed how the Town of Nags Head was not doing enough, both in educating people and enforcing the proper maintenance of individual properties' septic tanks. Participants recognized that maintenance was compromised by a rising groundwater table. However, participants said most citizens were not knowledgeable about the link between groundwater and septic systems. This was explained by one of our participants:

> *"I think that's a really big issue that I don't think a lot of people know about. And I think that it's kind of, not that anyone is trying to hide this information, I just don't think anyone's really thought about how disgusting or severe that could be and as time moves on, there's just more technology, more science, and studies to show that there could be a correlation and it's obviously unhealthy."*

The perceived knowledge gaps among Nags Head residents were deemed critical by our participants because they prevented action from being taken to address potential alternatives or ways to improve current septic systems.

Although not many were in favor of the town switching to a centralized wastewater treatment, most identified some potential benefits of doing so. One of the most frequently mentioned benefits was that water quality could be more easily monitored since, in contrast to individual oversight of septic tank systems, the responsibility would be on the town to oversee and maintain this system. Many participants agreed that centralized treatment would be beneficial for the environment and lessen the water quality hazards from flooding and associated septic contamination. While some of our participants were unsure about how septic systems were contributing to poor water quality, about the same amount of people believed that a switch to centralized treatment of wastewater would allow for the water to be treated better than how it is currently treated with onsite septic systems and would benefit water quality by avoiding the problem of failed septic systems, unsightliness, and wastewater overflowing into their yard during storms.

Barriers to Addressing Risk

While people recognized that there were potential water quality issues associated with septic tanks in a coastal landscape experiencing intense and frequent storms and a rising groundwater table, the majority of our participants believed that septic tank systems were less costly and worked better than alternatives, such as centralized wastewater treatment. Even though there were many complaints about having to fix or replace septic systems when they failed, there was little discussion about the cost of doing so, but cost was the most important factor for participants when they discussed centralized wastewater treatment. Participants expressed that they were already paying "exorbitant amounts" on their water bills:

> *"Well, I don't think because of the high groundwater that we could ever even have city sewage. And besides that, because of the costs and the risks would be overwhelming. I mean, whole communities have existed for decades and decades with septic fields. You build on a farmland, not like you're going to hook up to city sewage. It's cost prohibitive."*

This focus on cost of centralized wastewater treatment was expressed by nearly all of our participants. The majority did not know about the logistics or potential benefits of such a change, so cost was front of mind for them. Fizer (2016) similarly found cost was a key factor in decision making with regards to preferences for private well water over municipal systems. Some of the participants even acknowledged that their lack of information on this subject made them unfit to have an opinion on it.

Another factor that appeared to act as barrier to addressing the risks associated with septic tank systems was the way that septic systems were perceived to limit development and population density. Low population density was highly valued by our participants, and they made numerous references to how the Outer Banks was different than places like Myrtle Beach and Virginia Beach that are more built up and developed. One participant explained this view succinctly:

> *"And original founding values of the Town of Nags Head, I think the whole point of the septic was so that it couldn't become densely populated, so I'm not sure how going central would find ways to write policy that maintained that it didn't get overpopulated. I think the Town is trying."*

For participants like this one, widespread use of septic tank systems is what is keeping the Town from becoming densely populated and dotted with large hotels like Myrtle Beach. The participants had the perception that keeping the town on septic systems would prevent overpopulation and overuse of water resources. Even though many of them believed that development was already increasing, they believed that a switch to centralized wastewater treatment would lead to overdevelopment and more problems.

Although most participants were relatively uninformed about the logistics of switching to centralized treatment, they also expressed concern with the feasibility of such a project. It was a common belief that there was nowhere for a treatment plant to be built in Nags Head. One participant explained this:

> *"Because there's literally nowhere on the beach that you could put a central sewer system. You would have to have it piped at least 30 minutes away to be able to find the land that you could actually use to develop this system, so I'm just not even sure if that's a feasible thing."*

The barrier island could not support the infrastructure necessary for locating a centralized wastewater treatment facility. People attributed this to poor planning by the Town, as the required infrastructure simply did not allow for centralized treatment to exist there.

Overall, there seemed to a common perception among our participants within their discussions of wastewater treatment that residents of Nags Head were unwilling to make large-scale changes, such as switching to a centralized system. Participants explained that since most of the residents had always used a septic system, they would rather continue using something with which they are familiar. When asked about the willingness of the town residents to switch to centralized treatment, one participant explained this complication:

> *"Honestly, probably not very likely because I feel like people around here are very accustomed to how things are, and it takes a lot for change to happen, and then there's the whole issue about infrastructure already being there versus, I guess for the centralized one, you'd have to create something new. I think that would kind of be difficult for this area, but that's just a guess."*

Large changes, like switching to a different means of wastewater management, sound like they are not easy for this area. Their reluctance to change was partly influenced by the fact that they were not very knowledgeable about centralized wastewater treatment. Despite discussion of many problems associated with septic systems, participants were overall more focused on the short-term consequences of a switch to centralized treatment, mainly cost, rather than something that could be sustainable for the town moving forward. One participant described how there seemed to a "fix and replace" mentality where residents were more comfortable keeping their current system, even if it meant constantly needing to repair:

> *"It's such a pain in the ass because there's permits, there's this, there's that, there's the other thing. You've got to move this thing to one thing. You've got to crunch it down. You've got to do this. There's no sustainable solution. You're going to have to do it again. It's a 'fix and replace, fix and replace, fix and replace.' Get it sucked out, replace it, get it sucked out, replace it."*

In this participant's view, residents of Nags Head would currently rather deal with the known issues of septic system maintenance and repair than consider an unknown like conversion to centralized sewage treatment.

In addition to generally limited knowledge and information regarding wastewater and stormwater, another barrier to recognizing and minimizing the risks associated with changing environmental conditions in the Town of Nags Head described by several participants was a lack of reliable sources of information regarding septic tank systems and their maintenance. They reported that they received information on how to maintain their septic system from friends or local contacts, which may not always be reliable. Further, participants seemed to judge water quality on what they could physically see in the water, overwhelmingly attributing poor water quality to the presence of trash and plastics, rarity of fish sightings, and murkiness of the water. Based on appearances, participants assumed that the ocean and sound are healthy. Moreover, some participants stated that they believed the water quality of the ocean and sound was acceptable solely because they had not heard otherwise.

These knowledge gaps indicate the need for clear and easily accessible information regarding proper septic system management and for quantitative water quality indicators and data. The Town has already established the Septic Health Initiative to provide reliable information and encourage proper care of septic systems by property owners, and the Town indicates potentially hazardous ocean conditions with swimming bans, warning signs, and flags on the beach. However, these efforts do not appear to be filling knowledge gaps about wastewater treatment and water quality among participants. Until a full understanding of water quality and the factors that influence it exists among the residents of Nags Head, water quality will continue to be less than optimal and adaptation to changing environmental conditions will be delayed.

Responsibility

The previous themes delved into participants' perceptions about the problems associated with wastewater management and environmental change in Nags Head. This final theme encompasses participants' views about responsibility for addressing these problems. Responsibilities brought up by the participants ranged from homeowner septic tank maintenance to stormwater mitigation projects. Whether it was the participants expressing their own responsibilities as citizens, homeowners, business owners, environmentalists, or even the lack of ownership of responsibility of certain groups, it was a topic that came up, both prompted and unprompted, in the interviews.

While a vast majority of participants cited the importance of individual and the Nags Head community responsibility for wastewater treatment, they inextricably linked it to the responsibility of governmental agencies. When referencing community, the participants largely meant year-round residents and business owners in Nags Heads. A large number participants felt that even though it is up to individual homeowners or business owners to keep their septic systems up to standard, the financial burden is too great for them to handle on their own. Whenever a participant cited the responsibility of the individual for maintaining septic tanks on their property, they would later insist on the importance of governmental help in some form as well. In contrast, participants almost never stated that they thought stormwater management was the responsibility of individual property owners. This was the responsibility of the government. Often participants felt as though they were already doing everything they could for storms and flooding mitigation, both financially and within the law.

"Because if [the Town is] dealing with the septic systems, and they have to deal with everything else, then why not do that as well."

This participant illustrates these perceptions of the role of government and suggests a cohesiveness approach by the government would allow for better stormwater management.

Where participants cited a role for the community in responsible wastewater and stormwater management, it was largely in reference to community members banding together to change the current governmental infrastructure, as shown in the quote below.

"I think that citizens can come together to at least voice their opinion. I would like to think that would carry some weight or something. Especially if they're educated in the reality in water issues."

As demonstrated by the quote above, this participant believes that the Nags Head community is capable of making change by working together; however, this responsibility always ultimately comes back to the government.

Overall, the majority of participants concluded that wastewater and stormwater management is a responsibility that some form of government should have some level control over. This was often linked to the financial burdens of maintaining their septic tanks and properties after flooding events. The participants as a whole convey that voices will be heard by the government if they work together as citizens. Especially if the citizens took the time to "educate themselves" and understand the issues at hand, many of the participants believed this would be an effective way of making change happen in Nags Head. As mentioned previously in the first theme, the participants showed a strong sense of resilience. This character of resilience was demonstrated in the ways in which the participants conceptualized moving forward: through change.

The participants discussed three levels of government to which they attributed different levels of responsibility: The Town of Nags Head, Dare County, and the State of North Carolina. For the majority of our study participants, these governmental entities were logical choices for wastewater stormwater management because of their planning knowledge and funds. Town government was mentioned significantly more often than the county and state governments throughout all of the interviews. When Dare County and North Carolina State Government were discussed, it was only in negative contexts. This included statements that county and state funds went to the wrong projects or these entities simply did not care enough about these issues. Many participants expressed frustration with the North Carolina Department of Transportation for not allowing more outfalls.

The perceptions of the town varied heavily throughout the interviews as a whole, but nonetheless, the Town of Nags Head was the most common choice by participants for this management responsibility. Participants perceived the Town of Nags Head as having valuable knowledge of the area and the current wastewater and stormwater management in place, so it would be the logical choice for spearheading any changes moving forward. Conversely, a large number of our participants also strongly believed that the Town of Nags Head should change their management practices moving forward.

Participants suggested a wide variety of steps moving forward, ranging from new committees to tax breaks to limiting development. Despite these suggestions, knowledge about septic maintenance, previous projects done by the town, and overall environmental health varied widely among participants. While the majority of the participants had very strong opinions about how the Town of Nags Head was managing wastewater and stormwater, less than half of the participants accurately described the past or current projects, such as plans for lowering the outfall in the Gallery Row sub-watershed or the Septic Health Initiative. As a result, many of the participants were unable to give recommendations for further progress. Still, participants' perceptions of responsibility for wastewater and stormwater management in Nags Head revolved around government involvement, particularly the Town of Nags Head.

Conclusions and Implications

The home- and business-owners in and around the Gallery Row sub-watershed that we interviewed value Nags Head and the Outer Banks for a variety of reasons. A combination of connections to water, community, and resiliency revealed a strong sense of place among participants. These attachments to place and water and associated knowledge and experience positioned our participants to make observations of the community's vulnerabilities to environmental stressors. Participants cited increased storms, flooding, and climate change as drivers of concerning changes to water quality and quantity. These concerns translated into perceptions of risk of septic leachate, septic tank failure, and ultimately worsening of water quality. Although participants acknowledge these issues with current wastewater treatment systems, they expressed hesitation over centralized wastewater treatment citing costs, feasibility, lack of knowledge, and density development as barriers to change. Noting the tradeoffs between treatment methods and fear of large-scale change, the negatives associated with centralized treatment outweighed the current risks associated with septic systems for our participants. Addressing the perceived risks was thought to be the responsibility of the Town of Nags Head even though participants did note how they as individuals may improve their own wastewater treatment systems. These findings improve our understanding of how participants' value water quality, responsibility, and adaptation in Nags Head. These perceptions may impact future decision-making in Nags Head regarding wastewater treatment and environmental management policies.

Historical Water Level

Our analysis of historical groundwater level data from Nags Head aimed to determine whether water level in Nags Head had changed over seven years and if so, whether or not it has changed in a consistent pattern across the landscape of Nags Head. To analyze short-term changes in water level, we compared annual mean depths to groundwater to precipitation amounts, and we explored seasonal water levels that we expected would reflect summer increases in water use. We would expect that when there is higher precipitation, the DTGW would decrease, indicating that the water table was higher, or closer to the ground surface. Similarly, we would expect that when water use is greater, like in the summer tourism high season, that the depth to the groundwater in the sampling wells would be decreased because of the transfer of water from the confined aquifer (water withdrawal for household use) to the unconfined groundwater aquifer (where wastewater passes through septic systems and into the ground). By analyzing the depths to groundwater in subsets of wells based on drainage basins, we determined how the topography of the area may be influencing water-levels. To analyze the long-term changes in water level, we examined the trend in the mean DTGW across all eight groundwater sampling wells for seven years. We would expect that as sea-level rises, the DTGW in the groundwater wells of coastal Nags Head would decrease over time.

The groundwater sampling locations are named according to the closest neighboring streets. The dataset contained a total of 489 DTGW measurements from March 2011-June 2017 across eight historical groundwater wells located in Nags Head. From March 2011-June 2017, the minimum DTGW measurement of 4 in. was measured in the Juncos #1 groundwater well on April 9, 2012. Meanwhile, the maximum DTGW measurement of 150 in. was measured in the Nags Head Control groundwater well on March 14, 2011. See Appendix D for more summary statistics.

Elevation is an important factor because water generally runs downhill and can tell us how the groundwater level may be affected by precipitation, groundwater flow, and runoff. We would expect the mean DTGW to be greater in the higher elevation wells compared to the lower elevation wells. In Figure 7, we can see that at Nags Head Fire Station, one of the wells at higher elevation, the mean DTGW is greater than at the intermediate and low elevation wells. However, that same trend is inconsistent when analyzing the Nags Head Control groundwater well. The Nags Head Control groundwater well is located at the highest elevation, and thus, we would expect the mean DTGW to be greatest. Instead, the mean DTGW was large one year (2011), decreased by about 43% the following year (2012), and then remained pretty consistent through 2017.

At Old Cove #1 and Old Cove #2, both at the extreme low end of elevation, the mean DTGW was less than at the Nags Head Fire Station well, which is located at the extreme high end of elevation, but not as small as the mean DTGW of the intermediate elevation wells. In other words, the water table is closer to the ground surface in the intermediate elevation wells compared to the water table at either of the two elevation extremes, with the exception of Juncos #2. The Nags Head Control groundwater well is located at the highest elevation and the water table is closer to the ground surface than expected from 2012-2017. Old Cove #1 and Old Cove #2 are located on the lower end of elevation and the water table is farther from the ground surface than expected from 2011-2017. The Nags Head Control, Nags Head Fire Station, Old Cove #1 and Old Cove #2 groundwater wells are located on the west side of U.S. 158. Position relative to this major highway in north Nags Head may be a more critical driver of hydrology and DTGW than elevation.

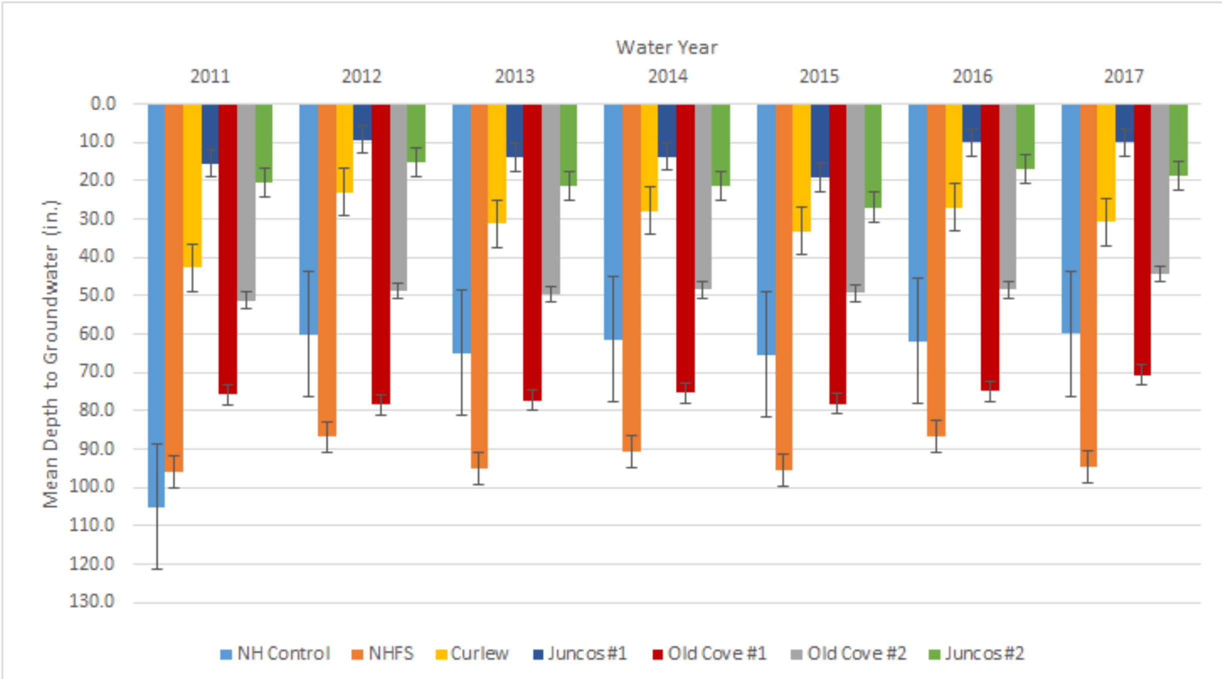

Figure 7: Mean DTGW by water year for seven of the eight historical groundwater wells in the Nags Head dataset. The Blackman Street well was not included in the figure because we only have three years of data from that location. The groundwater wells are organized by elevation with respect to sea-level. Nags Head Control (NH Control) and Nags Head Fire Station (NHFS) wells have the highest elevations, 28-30 ft. and 12-14 ft., respectively, and Juncos #2 has the lowest, with an elevation of 2-4 ft. However, Old Cove #1 and Old Cove #2 both have an elevation of 4 feet. Elevations were determined from a digital elevation model (DEM) with contour lines. The error bars represent each wells' standard deviation from the mean.

We assumed that median DTGW represented the baseline DTGW for each groundwater well for 2011-2017. We used the difference between mean DTGW by water year and the median to explore annual variability in DTGW at each groundwater well. We then compared annual mean deviations from the median to precipitation amounts to examine how precipitation affected the water levels in groundwater wells. Precipitation can supply more water to the unconfined aquifer layer through groundwater recharge thereby raising the water level and decreasing the DTGW. Additionally, if there is little precipitation in a year, then we would expect the DTGW to be greater, or the water level to be lower for that year. Figure 8 depicts a trend in our data that we would expect to see. When precipitation is low in 2011, the mean DTGW is greater than the baseline. When precipitation is higher in 2012, the mean DTGW is less than the baseline. While, Figure 8 depicts the relationship between precipitation, median DTGW, and annual mean deviations in DTGW from the median for the Curlew well, the Blackman, Nags Head Control and Nags Head Fire Station groundwater wells showed identical patterns. The relative precipitation (whether it decreases or increases by water year) corresponds with whether the annual mean DTGW is greater or less than the baseline, and that the DTGW is greater than the baseline in 2011 and then fluctuates between less than and greater than the baseline each subsequent year with a few exceptions. Both the Curlew and Blackman Street groundwater wells are on the east side of U.S. 158 on the north end of Nags Head and on the intermediate range of the elevation gradient while the Nags Head Control and Nags Head Fire Station groundwater wells are located on the west side of U.S. 158 on the north end of Nags head and at the extreme high end of the elevation gradient.

The trends in Juncos #1 and Juncos #2 were similar except where precipitation was highest in 2014, the mean deviation in DTGW from the median (baseline) was minutely above the baseline whereas we would have expected the higher precipitation to raise the water level causing the mean deviation in DTGW from the median to be below the baseline. Additionally, for Juncos #2, we would have expected the mean deviation in DTGW to be above the baseline for 2011 since precipitation was lower. However, it was slightly below the baseline. Both Juncos #1 and Juncos #2 are located in drainage basin 32 on the east side of NC 12 in south Nags Head and on the intermediate to lower end of the elevation gradient. Old Cove #1 and Old Cove #2 show the least amount of mean DTGW variability about the baseline for each water year and Old Cove #2 shows the least amount of variability overall. Both Old Cove #1 and Old Cove #2 are located in drainage basin 8 on the west side of U.S. 158 in north Nags Head and on the lower end of the elevation gradient. See Appendix D for similar figures depicting data for the other seven historical groundwater wells.

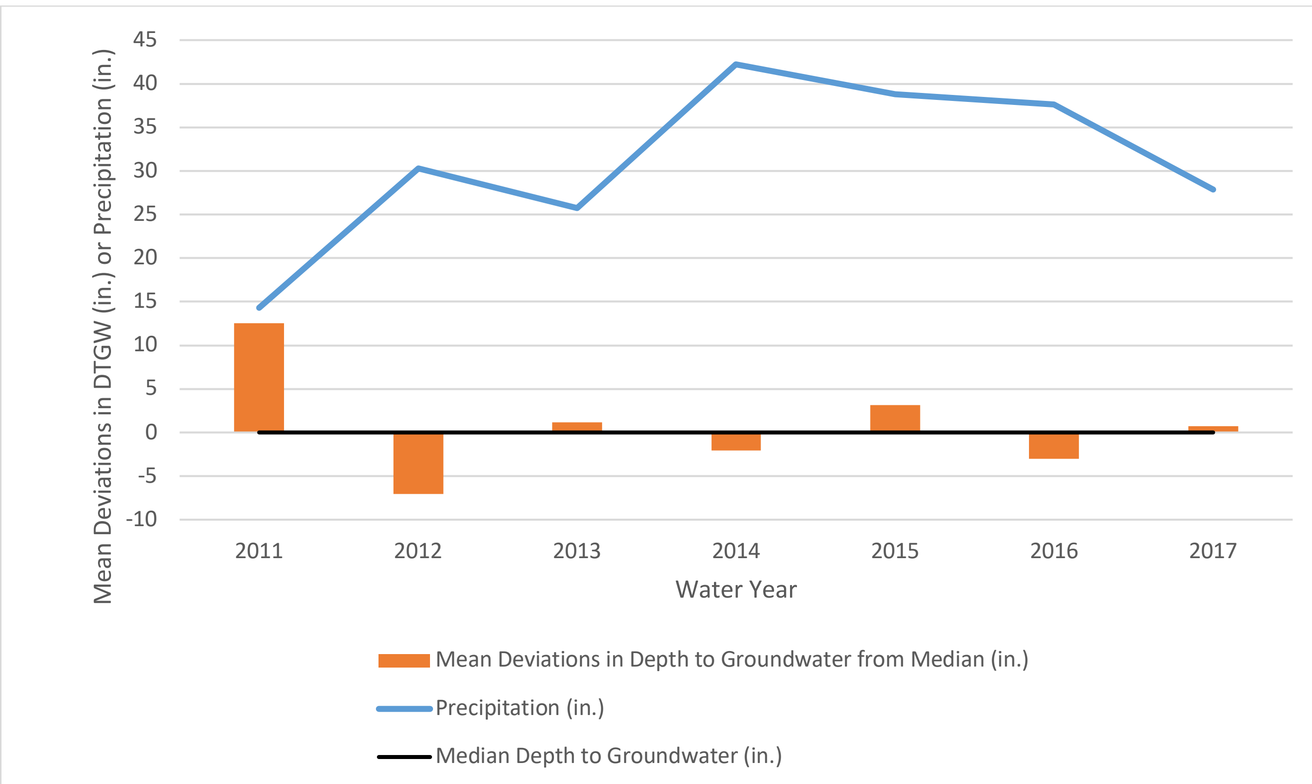

Figure 8: DTGW at the Curlew groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in DTGW from the median for each water year. The median serves as a baseline to compare DTGW for each water year and annual precipitation sums. The mean DTGW relative to the 2011-2017 median alternates from positive (indicating that water level is further from the ground surface) to negative (indicating that water level is closer to the ground surface) annually. DTGW has an inverse relationship with the sum of annual precipitation. Other historical groundwater wells in Nags Head showed similar patterns.

We expected that the large number of visitors during the summer would cause increased fluxes from the confined drinking water aquifer to the unconfined groundwater aquifer as a result of increased household water usage. We expected to see a decrease in the mean DTGW in all of the wells during the summer. However, perhaps confounding this expected pattern, there is increased evapotranspiration due to the increase in available solar energy and corresponding primary production in the spring and summer months.

In the summer dataset, the minimum DTGW was found in drainage basin 1 on August 29, 2012 (8 in.). The maximum was found in drainage basin 16 on June 6, 2017 (108 in.); see Appendix E for seasonal summary statistics. Figures 9, 10, 11, 12, 13, and 14 depict seasonal patterns of DTGW, which we expect to be impacted by water use and evapotranspiration. These figures are separated by their location in relation to the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head); Figures 9, 10, and 11 show data from locations east of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head)2 and Figures 12, 13, and 14 show data from locations west of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head). In Figure 9, 10, and 11, we see that the summer mean DTGW is greater (water table is lower) than expected for each water year across the drainage basins included in the study, with a few exceptions. If the data supported our hypothesis, we would expect to see a higher water level and a greater DTGW in the summer, especially for these drainage basins east of the major highway because they are in low-lying, flood-prone areas. Notably, all of the drainage basins located to the east of the major highway show an unexpected seasonal variability. The summer DTGW is larger than expected. This could be due to high rates of evapotranspiration in the summer. Meanwhile, the spring and fall seasons have an alternating increase and decrease of DTGW seen throughout the years. In Figures 12, 13, and 14, we see an unexpected seasonal variability. Figure 13 depicts a trend that we would expect to see where the summer DTGW is smaller across several water years, indicating a higher water table. Where this trend is not expressed, evapotranspiration in the summer could explain the greater DTGW in the summer causing the groundwater table to be lower than we expected.

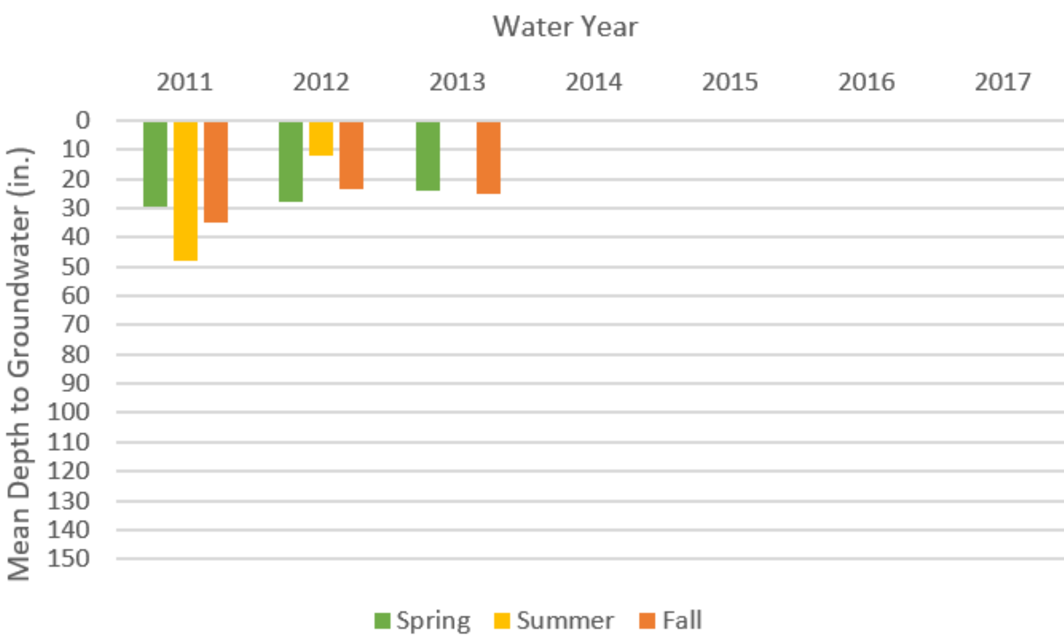

Figure 9: Historical DTGW measurements collected from drainage basin 1, Nags Head, NC from 2011-2017 expressed as mean DTGW for spring, summer, and fall by water year. Drainage basin 1 is located to the east of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head).

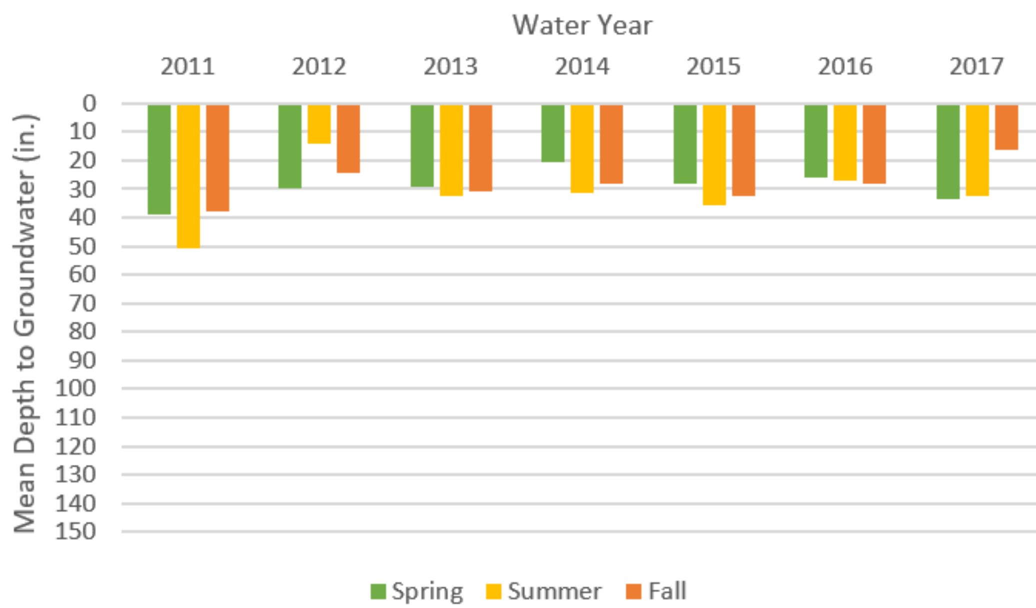

Figure 10: Historical DTGW measurements collected from drainage basin 2, Nags Head, NC from 2011-2017 expressed as mean DTGW for spring, summer, and fall by water year. Drainage basin 2 is located to the east of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head).

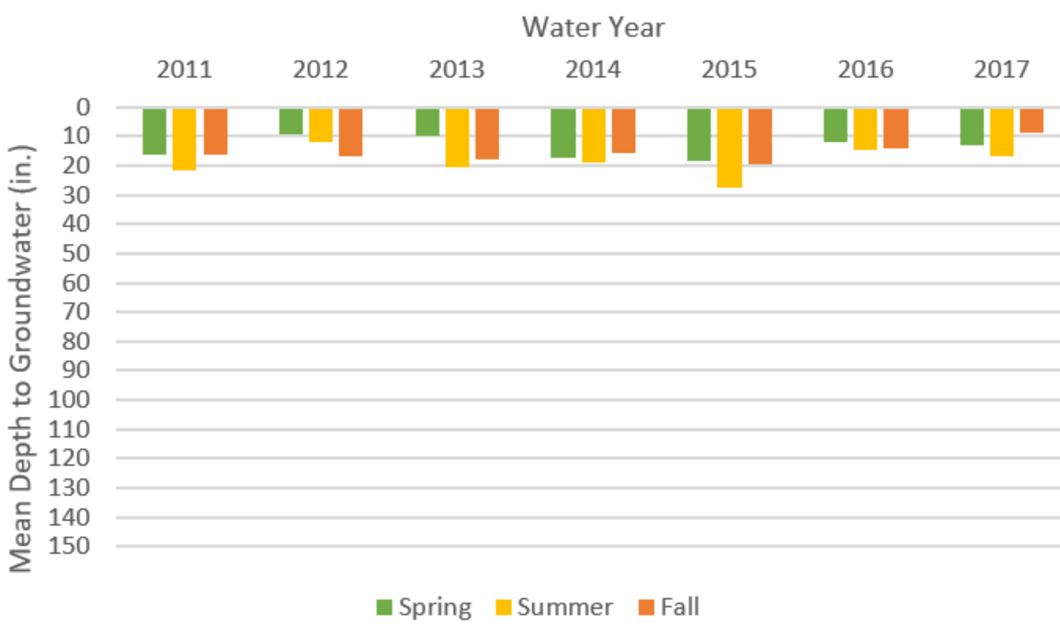

Figure 11: Historical DTGW measurements collected from drainage basin 32, Nags Head, NC from 2011-2017 expressed as mean DTGW for spring, summer, and fall by water year. Drainage basin 32 is located to the east of U.S. 158.

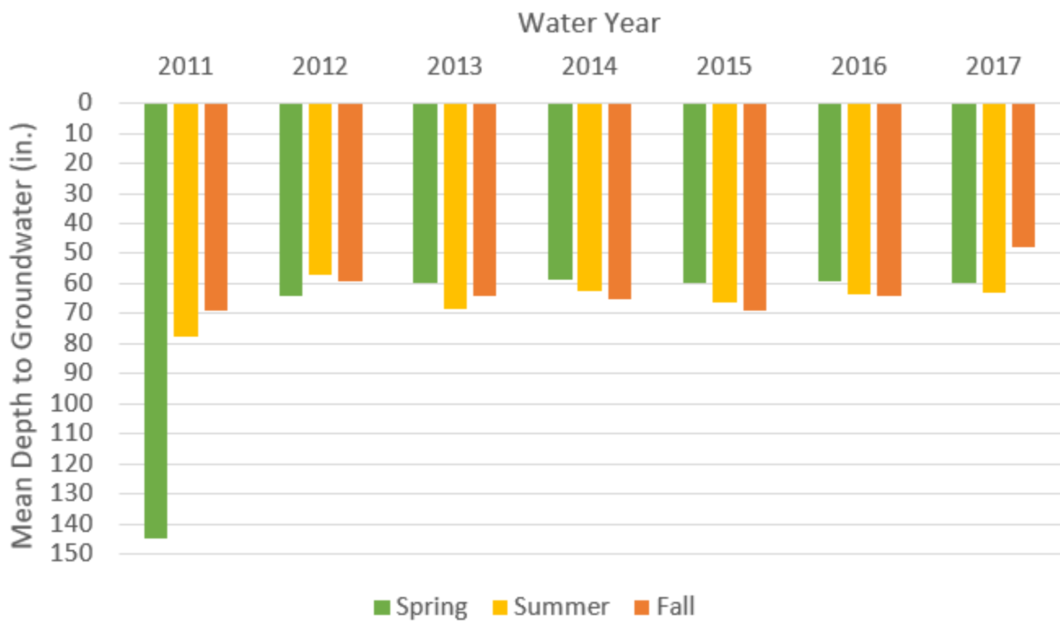

Figure 12: Historical DTGW measurements collected from Nags Head Control, Nags Head, NC from 2011-2017 expressed as mean DTGW for spring, summer, and fall by water year. Nags Head Control is located to the west of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head).

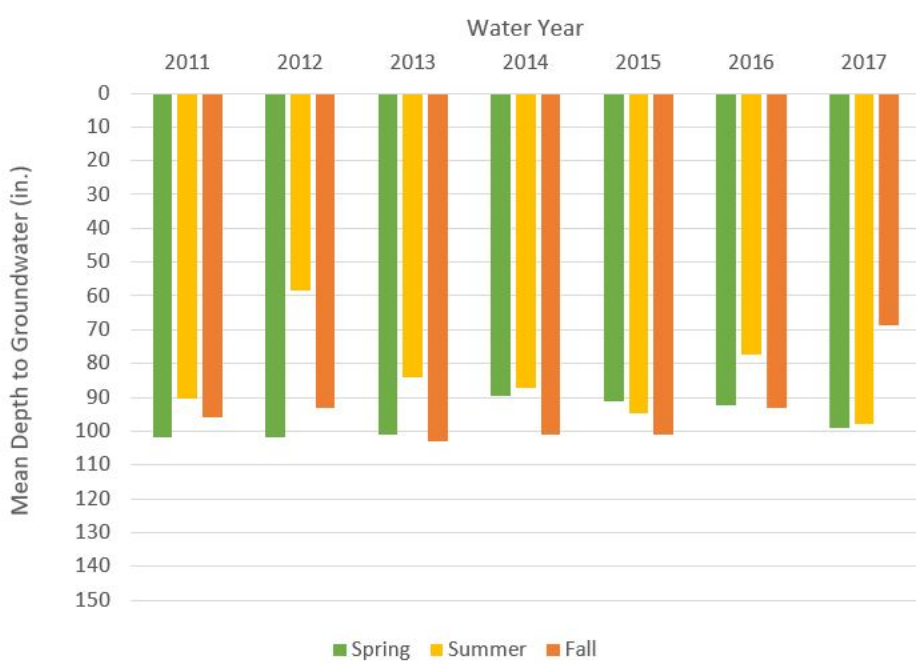

Figure 13: Historical DTGW measurements collected from drainage basin 16, Nags Head, NC from 2011-2017 expressed as mean DTGW for spring, summer, and fall by water year. Drainage basin 16 is located to the west of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head).

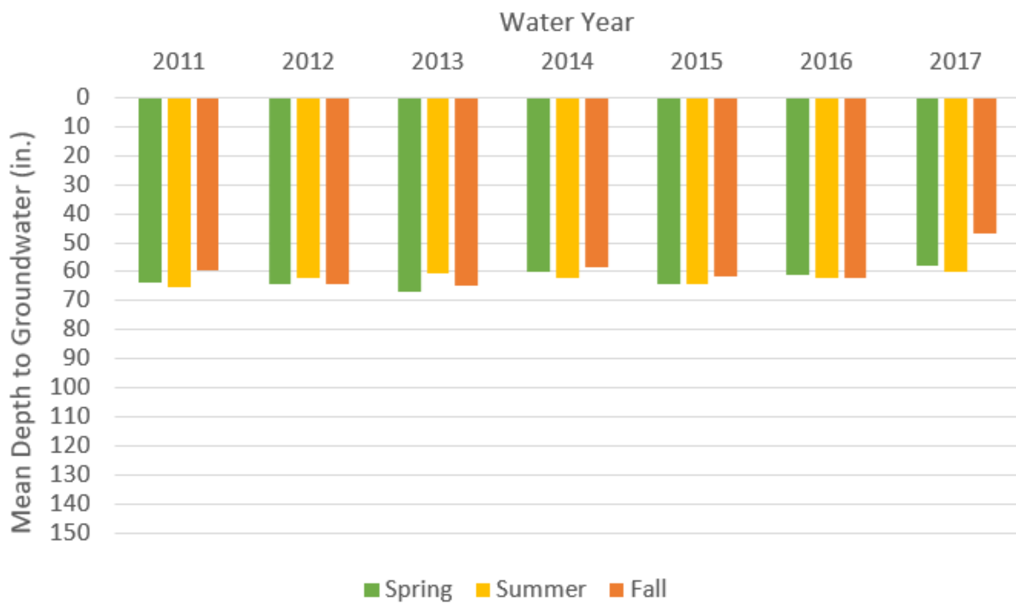

Figure 14: Historical DTGW measurements collected from drainage basin 8, Nags Head, NC from 2011-2017 expressed as mean DTGW for spring, summer, and fall by water year. Drainage basin 8 is located to the west of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head).

There is a negative linear relationship between water year and mean DTGW (Figure 15). In other words, the water level data is showing a slight increase over time. We used mean DTGW and the overall mean so that the analysis would encompass extreme events that a median would not. Despite the trend seen in Figure 15, the slight increase in the water level cannot be attributed unequivocally to sea-level rise because, when analyzing the impacts of sea-level rise, a 30-year tidal gauge record is advised in order to denote a relative trend in mean sea-level (Sea Level, 2016) and to differentiate between natural variability and sea-level influences. The annual rate of local relative sea-level rise measured at the Duck, NC NOAA Tidal Gauge is 4.55 mm/yr., or about 0.179 in/yr. This rate is based on monthly mean sea-level data from 1978-2017 and is defined as the change in sea height relative to land (NOAA, 2018). While it is understood that this rate could have affected our groundwater wells, we do not extract this rate from our analysis of annual mean DTGW because, based on location and elevation, sea-level rise cannot affect all of these wells at the same rate every year and we do not have a record long enough that we would expect to be able to pick out this trend. Assuming that Duck's annual rate of relative sea-level rise would be the same for Nags Head, if we know that the annual rate is 0.179 in., then we would have expected a 1.12-in. rise in sea-level from March 2011-June 2017, the length of our historical dataset. However, regional rates vary and depend on the geography, coastal circulation patterns and anthropogenic impacts of the area. Nonetheless, it is the local relative sea-level rise rate that affects coastal communities (Sea Level, 2016).

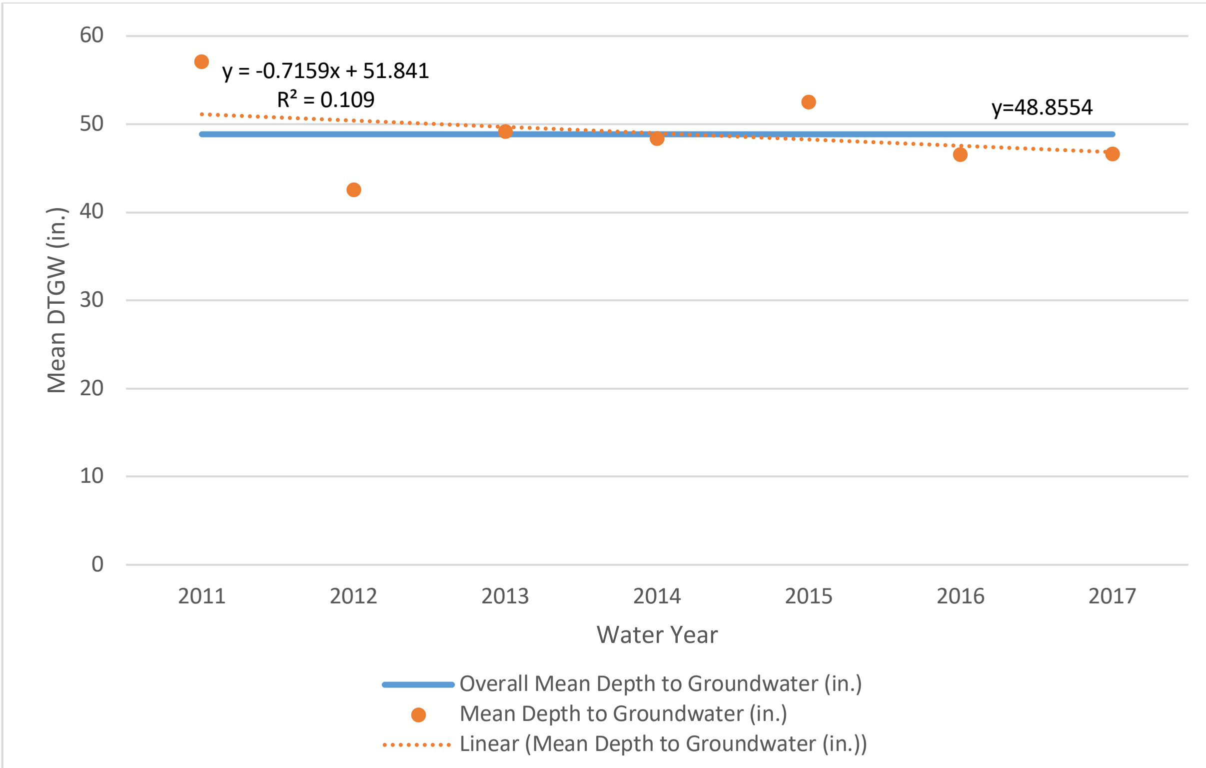

Figure 15: Mean annual DTGW from across all eight historical groundwater wells in Nags Head. The mean DTGW for all groundwater wells from 2011 to 2017 is 48.9 inches, which is depicted by a solid blue line. There is a negative linear relationship between water year and mean DTGW (R^2=0.109), which is depicted by the orange dashed line. The negative slope (-0.7159) shows that there is a slight decrease in mean DTGW, or a slight increase in water level, over time.

Our assumptions for this analysis were that the dataset represents water levels at each of the groundwater wells over time, both during baseline conditions and storm events, and that the sampled groundwater wells represent the water levels across the landscape of Nags Head. There is a weak, positive linear correlation (r=0.27; r^2=0.07) between sampling frequency in Figure 16 and the seasonal precipitation sums. This correlation is not as strong as expected based on interpretation of figures comparing annual mean precipitation and sampling occasions by season. However, there was limited winter sampling, irregular sampling intervals (in which some seasons included more sampling events than others) and an overall small number of sampling events. Nonetheless, in Figure 16 we can see that sampling frequency was greater at times when the precipitation was greater. We can see this to be true on multiple occasions. In the summer of 2014, the number of sampling events was greater and the seasonal precipitation sum was high. The same is true for the summer of 2015. However, where precipitation was high in the summer of 2012, the sampling frequency was low. More regular interval sampling throughout the year would help to capture more sampling events across a range of rainfall frequencies and amounts. Additionally, there is a moderate, positive linear correlation (r=0.43; r^2=0.19) between the season and sampling frequency. The variation in the number of sampling events throughout the seasons of any year indicates that sampling is inconsistent throughout the year. Over the entire dataset, there was only one winter sampling event and most of the sampling took place during the summer months. The dataset is limited in its representation of the water levels over time.

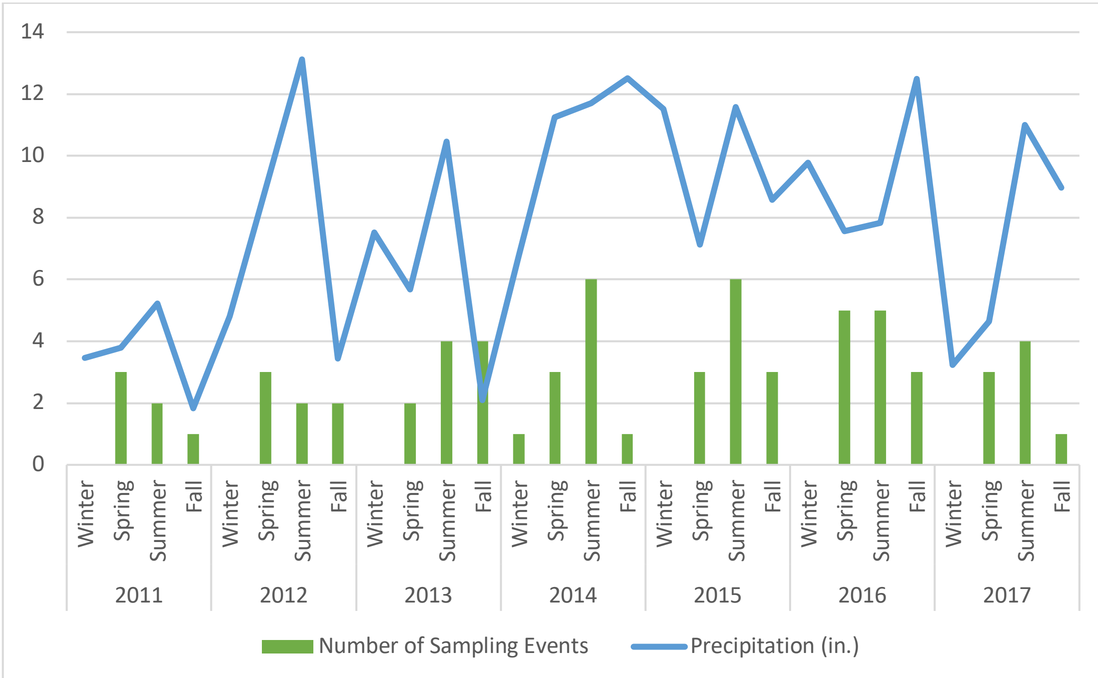

Figure 16: The total number of sampling events measuring DTGW for the historical groundwater wells in Nags Head from March 2011 to June 2017, categorized by season and water year. Precipitation is displayed as a seasonal sum. Monthly historical precipitation was summed by season.

Perhaps most noteworthy of our water level historical data analysis is the comparison of the DTGW to the recommended unsaturated soil depth. To the best of our knowledge, the Brunswick Bed in Fill wastewater disposal system is the predominant type of septic system in Nags Head. According to the County of Dare, Department of Health and Human Services (2017), the required separation from the bottom of a Brunswick Bed in Fill wastewater disposal system to the seasonal groundwater table is 24 inches to properly 'treat' the wastewater effluent is 24 in. for sand soils, which are the predominant soil type in Nags Head (County of Dare, 2017). According to the USDA, the typical depth below the surface of the ground to a septic system drain field is between 24 in. and 60 in. (USDA, 2016). The depth of a typical drainfield and recommended depth separation between the drainfield and groundwater means that if DTGW measurements are anywhere from less than 48 in. in the best case scenario to 84 in, in the worst, sewage effluent is likely not fully treated by percolation through unsaturated soil as recommended. Considering the entire historical dataset of 489 DTGW measurements for the eight groundwater wells, there were 239 DTGW measurements in which the depth to the groundwater was less than 48 in., which represents the best case scenario with regard to septic drainfields on the shallow end of the spectrum. In the worst case, where septic drainfields are found deeper in the soil (up to 84 in.), 428 DTGW measurements of the 489 were shallower than the recommended depth. This means that within our historical dataset of 489 DTGW measurements, there were between 239 to 428 potential instances where the groundwater table was high enough to not allow for this required separation from the bottom of the septic drain field and the top of the groundwater table.

Conclusions and Implications

When assessing the short-term changes in water level, we examined the annual mean water level at the eight historical groundwater wells and found that there was an inverse relationship between DTGW and the annual precipitation sum, with a few exceptions. We examined seasonal patterns in water use and determined that the season did not have an impact on the DTGW in the way that we expected. There was no suggestion that the increased tourism in the summer season caused a decrease in the DTGW as a result of bringing more water to the surface from the confined aquifer. When analyzing the long-term effects on water level, there was a slight decrease in the mean DTGW over the historical record, indicating a slight rise in the water table. However, we know that this slight increase in water level cannot be directed attributed to sea-level rise because we do not have the recommended 30-year tidal gauge record.

Finally, when thinking about the future of Nags Head, as house sizes and capacities increase, the septic system drain field size increases, as well (Friedman, 1998). Combining this with the increased development along the oceanfront in Nags Head (Town of Nags Head, 2017) and a decreasing depth between septic drainfields and the groundwater table due to sea level rise, we predict there to be an increasingly higher possibility for interaction between the groundwater and the septic system drain fields. This concern has the potential to become more severe if the DTGW decreases (the groundwater table rises) and the development of larger houses with more bedrooms and larger septic tank drain fields increases in the future.

In this analysis, we assumed that the data represented water level temporally and spatially in Nags Head. However, there was limited winter sampling, irregular sampling intervals (in which some seasons included more sampling events than others), and an overall small number of sampling events. Additionally, sampling across a range of rainfall frequencies and amounts was limited. For future sampling, we would recommend sampling at regular intervals throughout the year to encompass regular sampling across spring, summer, fall, and winter. Based on our analysis of water levels across the landscape, it seems that the groundwater wells are located in two types of hydrologic systems, one on the east side of the major highway (U.S. 158 in north Nags Head and NC 12 in south Nags Head) and one on the west side. The sampling locations represented by the dataset provide replicates exhibiting each of these hydrological conditions, by way of multiple drainage basins sampled, which is valuable. However, a more spatially intensive sampling across hydrological drainage paths within drainage basins on each the east and west side of the highway may better represent how precipitation and subsequent runoff and groundwater flow through drainage ditches affects water level during baseline conditions and during and after storm events.

Water quality field study

Nutrient and bacteria levels for storm and baseline conditions of surface waters (SW) and ocean water near an outfall pipe (OF) within the Gallery Row sub-watershed were compared to groundwater well controls (GW) and historical data from a surface water sampling site (Wrightsville #2; from 2011 to 2017). With the exception of nitrate, mean aggregate concentrations for all parameters were highest in SW samples after storm events compared to SW samples in baseline conditions and in the control GW wells. These results largely support our hypothesis that storm conditions would yield higher concentrations of nutrients and bacteria in SW sites than baseline conditions or GW sites.

Surface water sites consistently had a salinity less than 1 part per thousand (PPT) across all sampling dates. In SW samples, temperatures decreased by nearly 10°C from the first sampling date (Oct. 5, 2018; 22.3°C – 24.5°C) to the last sampling date (Oct. 27, 2018 16.3°C – 16.5°C) whereas GW samples remained relatively constant. (See Appendix G for additional environmental data).

Baseline nitrate levels across sample locations range from 1.19 µg-N/L at sample site GW1 during baseline conditions 830 µg-N/L at site GW2 during baseline conditions **(Figure 17)**. This range of values is greater than that observed by Mallin et al. (2013) on the Cape Hatteras National Seashore, where average nitrogen values ranged from 12 to 71 µg-N/L. The mean nitrate concentration in samples from GW2 is higher than any other mean nitrate concentration regardless of whether during a baseline or storm event. These results are unexpected as GW2 was chosen as a control. There may be unknown natural or anthropogenic sources of nitrate contributing to the high concentrations of nitrate observed at site GW2, rendering GW2 a poor control site for nitrate. Surface water 2 had the highest nitrate concentrations among the SW samples and the largest standard deviation. This range of concentration values in the standard deviation may reflect point-source contributions of nitrate to SW2, such as from wildlife or domestic animal excrement.

Nutrients

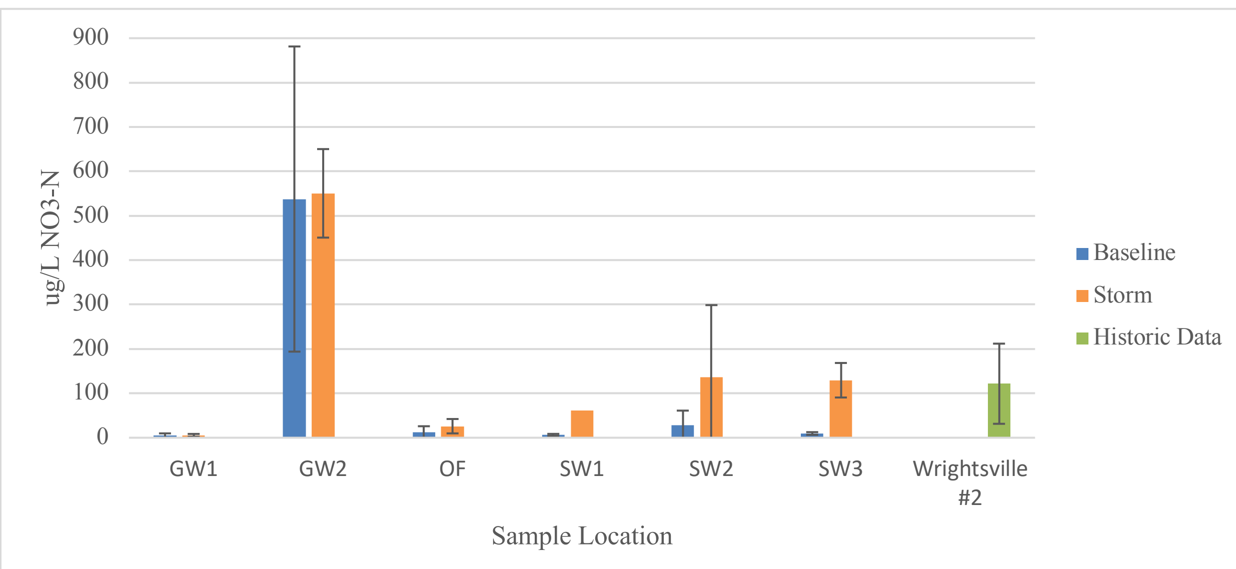

Figure 17: Mean nitrate concentrations (µg/L) across baseline (absent of rainfall events) and storm data for samples collected from sampling locations in Nags Head, NC in October 2018. Historical data from Wrightsville #2 historical data (2011-2017) is also depicted for reference. Error bars represent one standard deviation from the mean. SW1 does not have error bars as the site was only sampled once during a storm event due to low or absent water levels during sample time.

Nitrate concentrations were higher during and following the storm event compared to baseline conditions across all SW sites (Figure 18) but were not affected by storm conditions at the control GW sites. There may be unknown natural or anthropogenic sources of nitrate contributing to the high concentration of nitrate observed at site GW2: this site is in a residential location with large amounts of impervious surface such as driveways, and Jockey's Ride, a state park, is located nearby. These surfaces may funnel nitrate-rich effluent, such as lawn fertilizer and animal waste, to the GW2 site, thereby artificially increasing nitrate concentrations and rendering GW2 a poor control site for nitrate. SW2 had the highest nitrate levels of the SW sample locations with a large standard deviation. This range of concentration values in the standard deviation likely reflect nitrate being added to SW2 from point sources, such as wildlife or pet animal excrement. Increased nitrate levels during the storm event could have also resulted from storm runoff and contaminants in septic drain fields. This is due to the fact that nitrate is present in septic leachate, and even fully functioning septic systems do not considerably reduce nitrogen levels in effluent.

The mean nitrate concentrations of historical data from 49 sample dates between the years 2011-2017 for historical Wrightsville #2 SW data is within one standard deviation of the SW sample means (Figure 17), indicating that our SW data falls within the range of data collected over a longer period of time and across fall, spring, and summer seasons, and historical data might be influenced by similar nitrate sources.

Figure 18 compares mean aggregate nitrate concentrations of all SW sites in both baseline and storm conditions to mean aggregate nitrate concentrations of groundwater control sites. As hypothesized, nitrate levels increased during and following the storm event relative to the baseline conditions (Figure 18). The large mean from the GW sample site in Figure 18 results from the abnormal nitrate levels observed in GW2 (Figure 17). The standard deviation of the storm data is larger than that of the baseline data, reflecting greater variability within SW sites under storm conditions than under baseline conditions, suggesting that spatially discrete point sources, such as wildlife and domestic animal excrement, contributed nitrate to nearby surface water sites during storm events. The smaller standard deviation exhibited by surface water sites in baseline conditions suggests a persistent baseline source of nitrogen in SW locations.

Our observed orthophosphate values were found to be considerably lower than that of Mallin et al. (2013) with a mean baseline value of 23.53 μg/L and mean storm value of 59.52 μg/L. The mean orthophosphate concentration observed by Mallin et al. (2013) across sample sites is 127 μg/L. Similar to discussion by Mallin, these nutrients can be attributed to sewage and/or wild animal feces, and more data (such as year-round sampling and corresponding municipal water usage data) are needed for further conclusion.

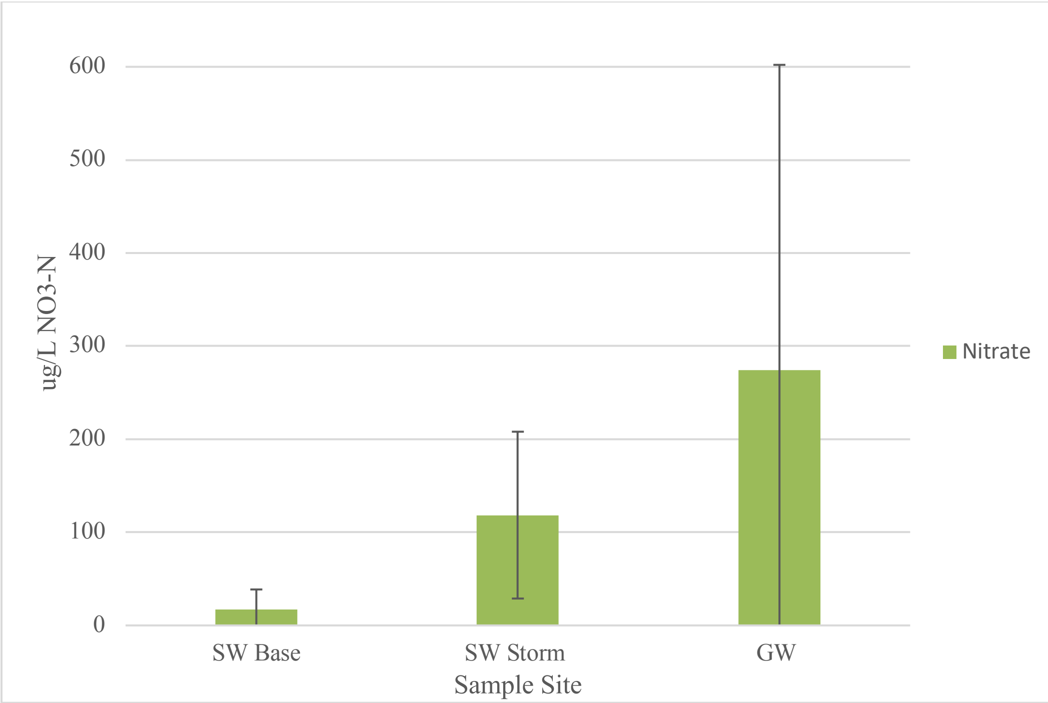

Figure 18: Mean aggregate nitrate concentrations (µg/L) across corresponding dates and sampling locations for SW baseline, SW storm, and GW control samples collected from sampling locations in Nags Head, NC in October 2018. Error bars represent one standard deviation from the mean.

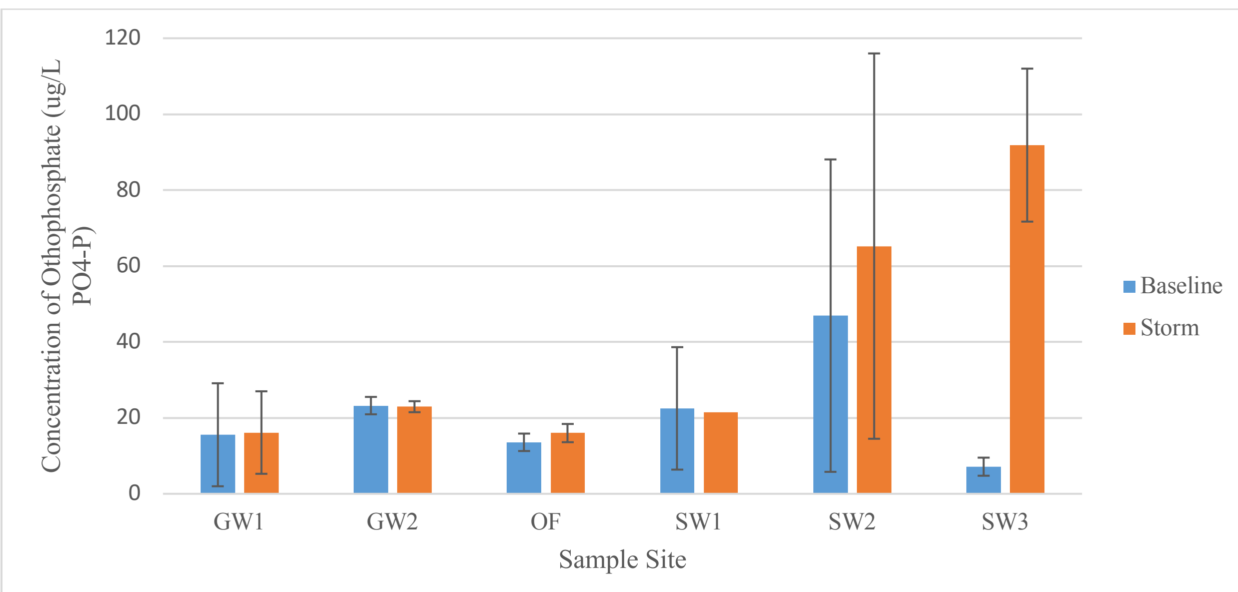

Figure 19: Mean orthophosphate (µg/L) concentrations across baseline (absent of rainfall events) and storm data for samples collected from sampling locations in Nags Head, NC in October 2018. Error bars represent one standard deviation from the mean. SW1 does not have error bars as the site was only sampled once during a storm event due to low or absent water levels during sample time.

With the exception of SW1, a higher mean orthophosphate concentration was observed at all sample locations during and following the storm event compared to baseline conditions (Figure 19). Observed concentrations at SW3 under storm conditions were the highest among all sample sites and had the largest increase from baseline to storm sampling (Figure 19). SW2 data in both baseline and storm conditions have the largest standard deviations, again, perhaps suggesting spatially discrete but temporally variable point sources contribute orthophosphate. Standard deviations are much smaller in GW1, GW2, and OF. Additionally, standard deviations of storm and baseline conditions within the same site overlapped closely at GW1, GW2, and OF, suggesting that the differences in concentrations between storm and baseline conditions within the same site were not statistically significant.

Figure 20 compares mean aggregate orthophosphate concentrations in SW sites in both baseline and storm conditions to mean aggregate orthophosphate concentrations in groundwater control sites. As the hypothesis predicted, orthophosphate concentrations are greater in storm conditions than in baseline conditions (Figure 20). The large error bars exhibited in both SW storm and baseline data reflects greater variation in orthophosphate concentrations from the mean. GW control concentrations are lower than both SW baseline and SW storm values. The smaller error bars indicate that concentrations vary less in GW sites than in SW sites, suggesting that orthophosphate may be entering groundwater sites at more constant concentrations and rates.

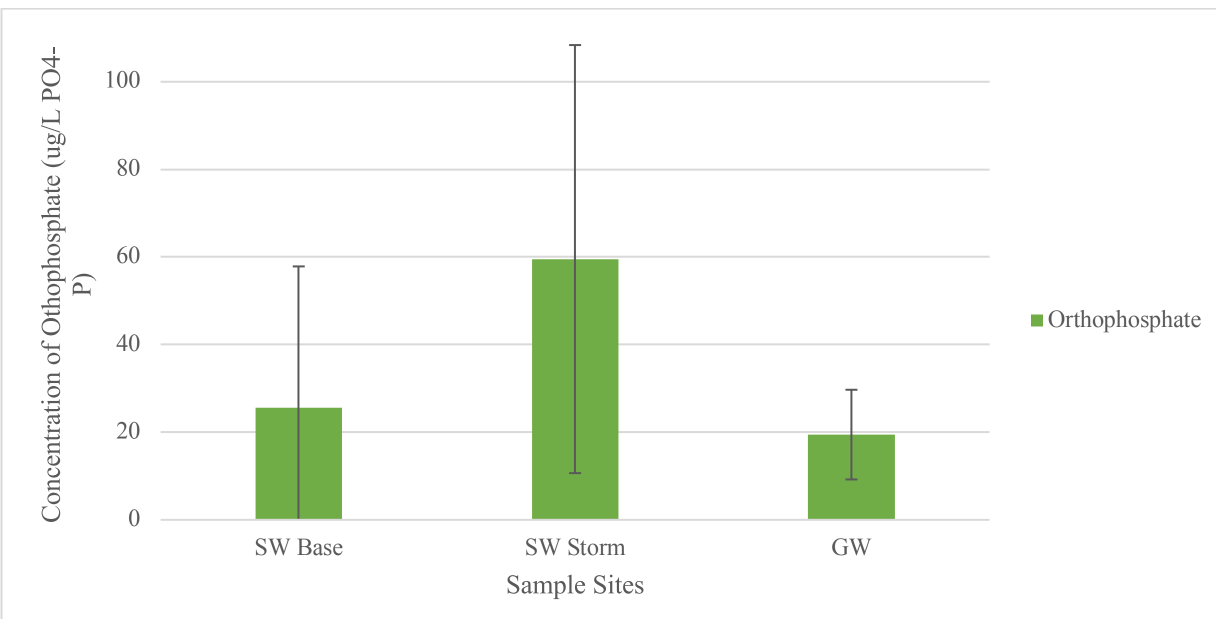

Figure 20: Mean aggregate orthophosphate concentrations (μg/L) across corresponding dates and sampling locations for SW baseline, SW storm, and GW control samples collected from sampling locations in Nags Head, NC in October 2018. Error bars represent one standard deviation from the mean.

Observed ammonia concentrations in our study fall more closely within ranges observed by Mallin et al. (2013) of 37-253 μg/L. Mallin et al. (2013) emphasizes the relationship between ammonia concentrations and municipal water usage, as the study found ammonia concentrations increased with water usage. Our study did not investigate this relationship as samples were taken over the month of October, following the peak tourist season in summer. Mallin et al. (2013) and our study both observed ammonia concentrations to increase following precipitation (Figure 21), suggesting ammonia loading from septic leachate as ammonium is a byproduct of sewage (Mallin et al, 2013).

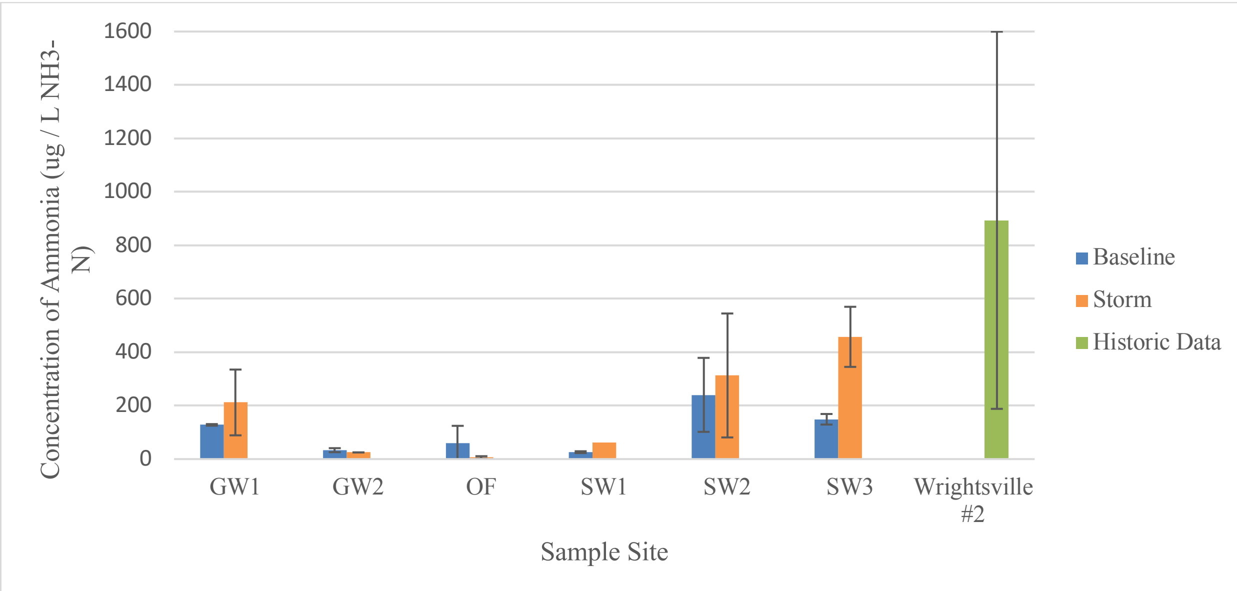

Figure 21: Mean ammonia concentrations (μg/L) across baseline (absent of rainfall events) and storm data for samples collected from sampling locations in Nags Head, NC in October 2018. Wrightsville #2 historical data (2011-2017) is also depicted for reference. Error bars represent one standard deviation from the mean SW1 does not have error bars as the site was only sampled once during a storm event due to low or absent water levels during sample time.

At most sites aside from GW2, ammonia concentrations were greater during and following the storm event than under baseline conditions (Figure 21). However, this was not the case for GW2, which showed no change in concentration between baseline and storm conditions, and OF, which showed a higher concentration under baseline conditions than under storm conditions. Although GW2 had high nitrate concentrations, its mean ammonia concentration was among the lowest (Figure 21), demonstrating the relationship between ammonia and nitrate, as ammonia is converted into ammonium then nitrate by nitrifying bacteria in an aerobic environment. Standard deviations for SW2 under both baseline both baseline and storm conditions, as well as SW3 and GW1 under storm conditions, were appreciably large, suggesting that these sites received ammonia inputs at irregular concentrations and rates, perhaps from a nearby point source. The large value corresponding with historical data from SW site Wrightsville #2 may be attributable to higher ammonia concentrations during the times of year when the population density in Nags Head increases during the tourism season in the summer months, which is not captured in our October data. SW1 does not have error bars as the site was only sampled once during a storm event due to low or absent water levels during sample time. OF was the only sample location to experience a decrease in mean ammonia concentrations during a storm event and has a small standard deviation. This decrease may be attributed to a dilution of ammonia by ocean water, as well as variations in exactly where the sample was collected in relation to changing currents surrounding the outfall pipe that carry effluent.

Figure 22 compares mean aggregate ammonia concentrations in SW samples in both baseline and storm conditions to mean aggregate ammonia concentrations in GW control samples. As the hypothesis predicted, ammonia concentrations at SW sites under storm conditions are greater than ammonia concentrations at both SW sites under baseline conditions and GW control sites. The large standard deviation exhibited in surface water storm data shows that ammonia concentrations varied in storm conditions, suggesting that the ammonia is sourced from point sources at irregular concentrations and rates. Overlapping error bars between all 3 aggregates suggest that the variations in concentrations are within a similar range of each other.

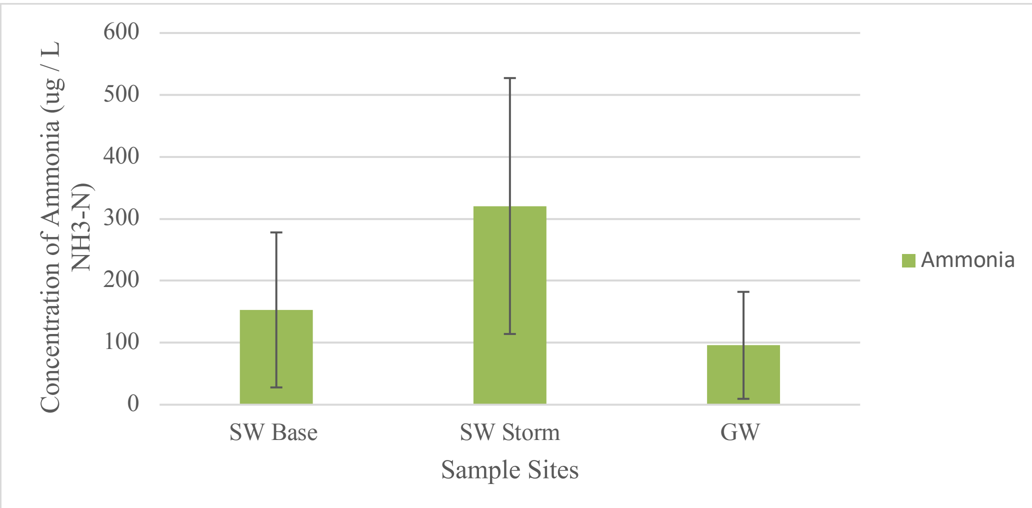

Figure 22: Mean aggregate nitrate concentrations (µg/L) across corresponding dates and sampling locations for SW baseline, SW storm, and GW control samples collected from sampling locations in Nags Head, NC in October 2018. Error bars represent one standard deviation from the mean.

Bacteria

Figure 23 depicts the mean *Enterococcus* concentrations (CFU) of samples from each sampling location and mean historical *Enterococcus* concentration of surface water at Wrightsville #2 in Nags Head (2011-2017). As the hypothesis predicted, mean *Enterococcus* concentrations are much higher after storm events than during baseline conditions for all surface water sites. This was not the case for the groundwater sites nor for the outfall site, all of which contained virtually no *Enterococcus* in both baseline and storm conditions. The Wrightsville #2 site also reported very little *Enterococcus* compared to surface water sites after storms. This could be due to the fact that data from this site was not explicitly collected after storm events, thereby underreporting *Enterococcus* concentrations. Alternatively, it may be the case that Wrightsville #2 was comparatively cleaner when samples were taken in years past than other surface water sites in the Gallery Row watershed are now, possibly suggesting greater interactions between surface water and pollutant sources, such as septic leachate, at present. The standard deviations of SW2 in storm conditions and SW3 in both baseline and storm conditions are large, exhibiting large variations in *Enterococcus* concentrations at these sites. This could be attributable to point sources of enterococcus that add bacteria to these sites at irregular concentrations and rates, such as animal excrement.

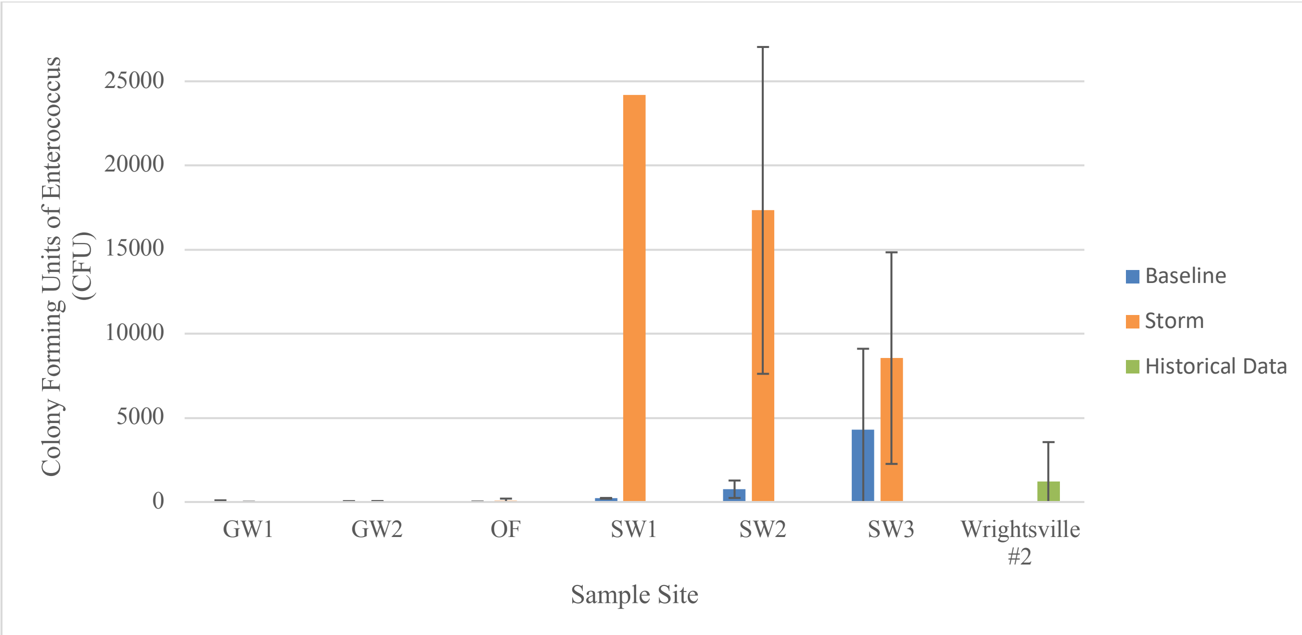

Figure 23: Mean *Enterococcus* concentrations (CFU) across baseline (absent of rainfall events) and storm data for samples collected from sampling locations in Nags Head, NC in October 2019. Historical data from Wrightsville #2 historical data (2011-2017) is also depicted for reference. Error bars represent one standard deviation from the mean. SW1 does not have error bars as the site was only sampled once during a storm event due to low or absent water levels during sample time.

Figure 24 compares the mean *Enterococcus* concentrations of each sample site at baseline conditions and the mean historical *Enterococcus* concentrations of SW at Wrightsville #2 with the EPA threshold for allowable *Enterococcus* concentrations in recreational waters. EPA standards for *Enterococcus* concentrations are 35 CFU/100 mL for marine recreational waters and 33 CFU/100 mL for fresh recreational waters (EPA 2018). The EPA threshold has therefore been adjusted accordingly for the outfall (OF) site as this is the only marine water sample in the study. In baseline conditions, *Enterococcus* concentrations in GW and OF samples fall below this standard, suggesting that these waters are suitable for recreational use. In all SW sample sites at baseline conditions and at the historical site, however, *Enterococcus* concentrations exceeded EPA standards for concentrations in recreational waters, with concentrations decreasing with distance to the ocean coast. The standard deviation bars for SW1 and SW3 at baseline conditions are small and do not overlap, suggesting that each site derives their *Enterococcus* concentrations from constant or non-point sources with little variation, such as excrement from wildlife or domestic dogs. Of these SW sites, SW2 exhibited greater variation and overlapped with Wrightsville #2 data's standard deviation, suggesting that SW2's *Enterococcus* concentrations correspond more closely to historical concentrations and variations, and that it may be receiving *Enterococcus* from non-point sources. While the surface water drainage ditches where the surface water data were collected are not technically considered to be recreational waters, children frequently play in flooded streets with drainage ditches adjacent to them. Given that these waters exceed EPA *Enterococcus* standards by a significant margin at baseline conditions, with storm concentrations being higher still as seen in Figure 23, these waters may pose a significant public health risk to the town of Nags Head, particularly during storm events.

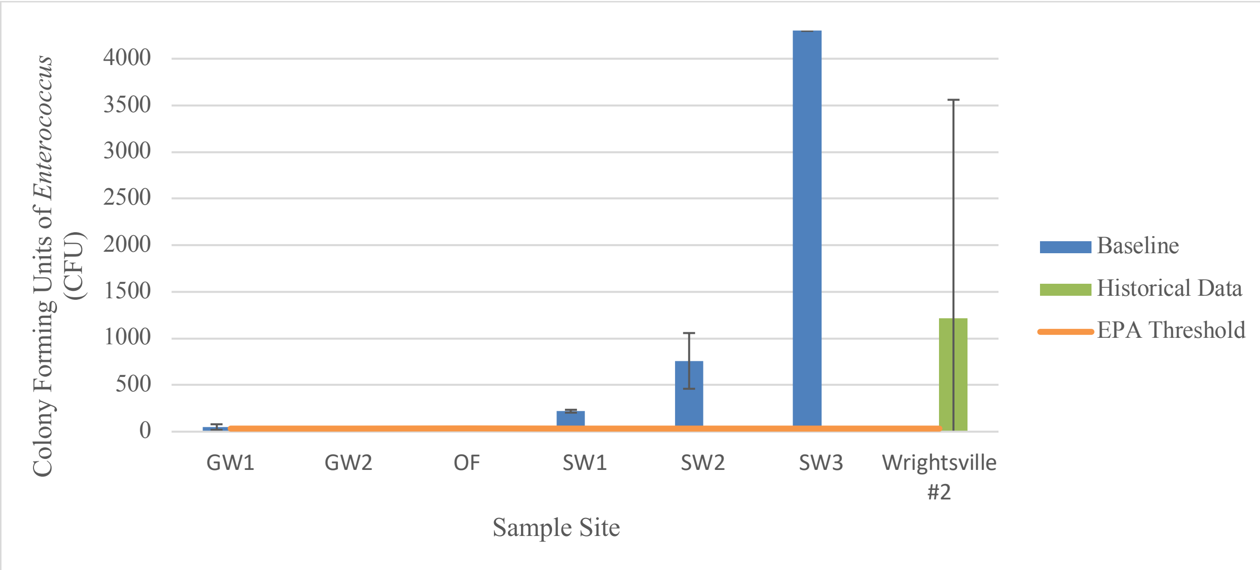

Figure 24: Mean *Enterococcus* concentrations (CFU) across baseline (absent of rainfall events) dates for samples collected in Nags Head, NC in October 2018 as compared to the EPA threshold for enterococcus concentrations (CFU) in recreational waters. Error bars represent one standard deviation from the mean.

Figure 25 compares mean aggregate *Enterococcus* concentrations in SW samples in both baseline and storm conditions to mean aggregate *Enterococcus* concentrations in GW control samples. As the hypothesis predicted, SW sites under storm conditions yield much higher *Enterococcus* concentrations than both SW sites under baseline conditions and GW sites, the latter of which showed nearly no bacteria. Additionally, the standard deviation of SW data during and following a storm is larger than that of SW baseline data, indicating much greater variation in SW *Enterococcus* concentrations under storm conditions than under baseline conditions. The standard deviations of storm and baseline data do not overlap, suggesting that the differences between the two concentrations are statistically significant and that the sources of *Enterococcus* may differ under each condition.

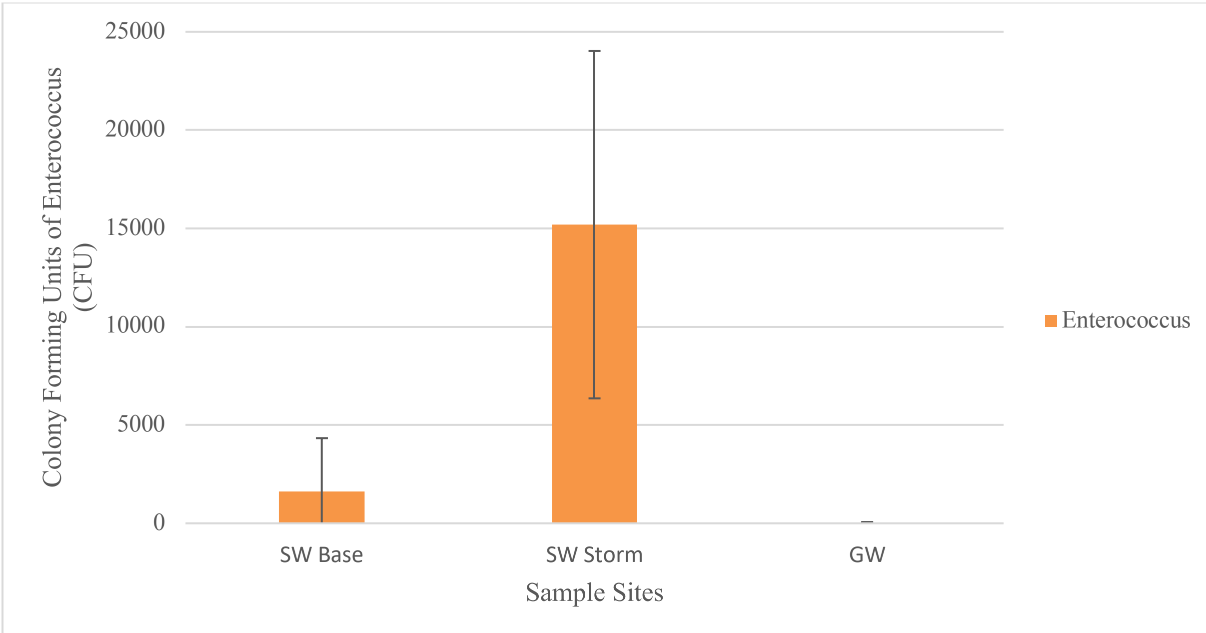

Figure 25: Mean aggregate *Enterococcus* concentrations (CFU) across corresponding dates and sampling locations for SW baseline, SW storm, and GW control samples collected from sampling locations in Nags Head, NC in October 2018. Error bars represent one standard deviation from the mean.

As the hypothesized, GW sites have virtually no *E. coli* present while two of three surface water sites have appreciable *E. coli* concentrations in baseline conditions, and all three surface water sites have drastically increased concentrations under storm conditions during and following the storm event (Figure 26). Storm concentrations of *E. coli* decreased as distance to the ocean decreased, suggesting that pollutants are more concentrated in storm waters farther inland than in waters closer to the ocean outfall since salinity did not differ between dates or locations for SW sites. Although there was insufficient data to calculate standard deviation for SW1 in storm conditions, SW2 and SW3 storm data exhibited appreciable variation. This suggests that SW2 and SW3 likely received *E. coli* from similar point sources in storm conditions, such as animal excrement. The standard deviations of SW2 and SW3 in baseline conditions, as well as the standard deviation of SW3 in storm conditions, overlapped with variance range of Wrightsville #2. This suggests that the *E. coli* concentrations of SW2 and SW3 roughly correspond with those recorded in the past in surface waters of Wrightsville #2. Additionally, the standard deviations of *E. coli* concentrations at SW3 storm conditions overlapped with the standard deviations of SW3 in baseline conditions and SW2 in both storm and baseline conditions. This suggests that the differences in concentrations between SW3 storm and the three aforementioned concentrations may not be statistically significant, indicating that they may receive *E. coli* from similar types of sources.

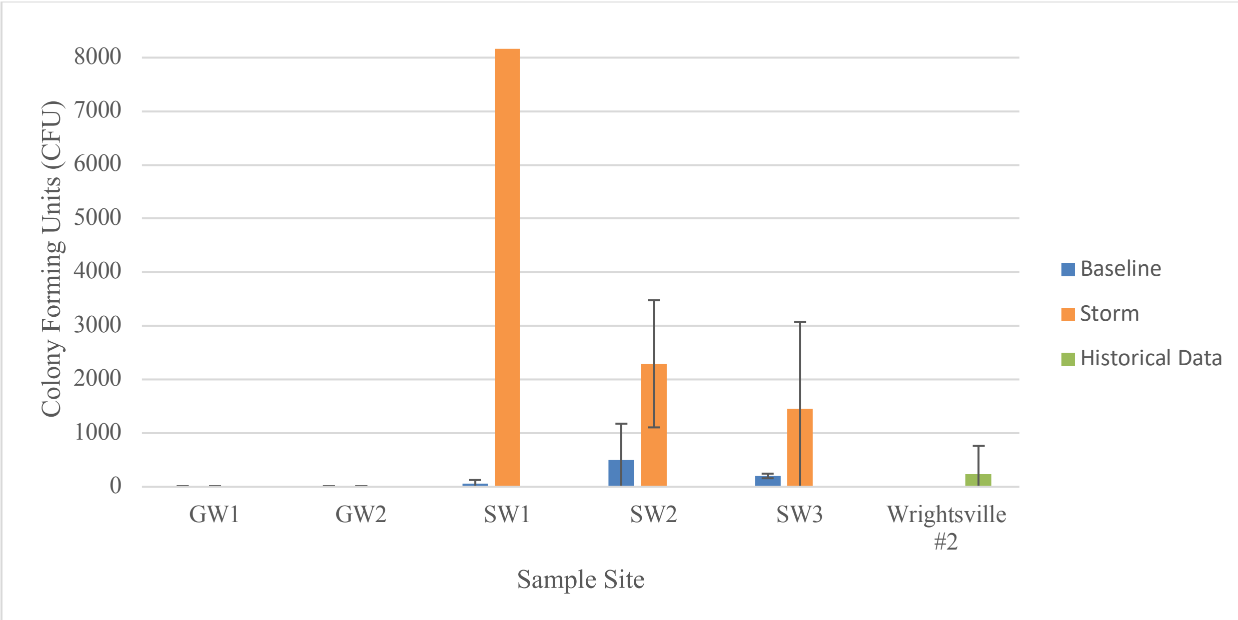

Figure 26: Mean *E. coli* concentrations (CFU) across baseline (absent of rainfall events) and storm data for samples collected from sampling locations in Nags Head, NC in October 2018. Historical data from Wrightsville #2 historical data (2011-2017) is also depicted for reference. Error bars represent one standard deviation from the mean. SW1 does not have error bars as the site was only sampled once during a storm event due to low or absent water levels during sample time.

Figure 27 compares the mean aggregate *E.coli* concentrations of all sample sites except OF at baseline conditions and the mean aggregate historical *E.coli* concentrations of SW at Wrightsville #2 with the EPA threshold for allowable *E.coli* concentrations in recreational waters. OF has been excluded because it is a saltwater site and *E.coli* is used as a bacterial indicator for water quality only in fresh recreational waters. EPA standards for recreational freshwater require *E. coli* concentrations to be below 126 cfu/100 mL (EPA 2018). At baseline conditions, both GW sites and SW site #1 fall below the threshold while SW2 and SW3 and the Wrightsville #2 exceed the threshold. Though SW2 has the highest *E.coli* concentration, it experiences less variation than SW1 and SW3, which both exhibit very large standard deviations compared to their relatively small *E.coli* concentrations. Furthermore, the standard deviations of SW1 and SW3 overlap with one another and with Wrightsville #2, suggesting that current *E.coli* concentrations in surface waters in Nags Head are within the same range as historical concentrations. While the SW drainage ditches where the SW data were collected are not technically considered to be recreational waters, children frequently play in flooded streets with drainage ditches adjacent to them. Given that these waters exceed EPA *E.coli* standards by a significant margin at baseline conditions, with storm concentrations being higher still as seen in Figure 26, these waters may pose a significant public health risk to the town of Nags Head, particularly during storm events.

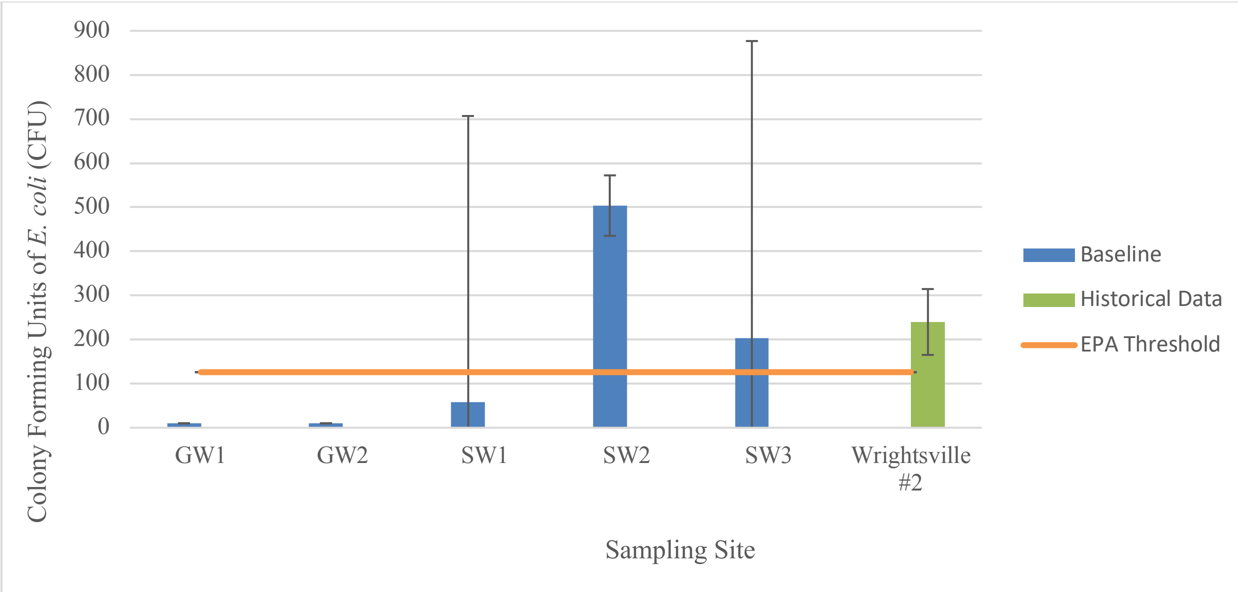

Figure 27: Mean *E. coli* concentrations (CFU) across baseline (absent of rainfall events) dates for samples collected in Nags Head, NC in October 2018 as compared to the EPA threshold for enterococcus concentrations (CFU) in recreational waters. Error bars represent one standard deviation from the mean.

Figure 28 compares mean aggregate *E. coli* concentrations in SW sites in both baseline and storm conditions to mean aggregate *E. coli* concentrations in GW sites. As the hypothesis predicted, SW sites during or following a storm event yield much higher *E. coli* concentrations than both SW sites under baseline conditions and GW sites, the latter of which showed almost no bacteria. Additionally, the standard deviation of SW storm data is larger than that of SW baseline data, suggesting much greater variation in surface water *E. coli* concentrations under storm conditions than under baseline conditions. The standard deviations of both SW storm and baseline data do overlap somewhat, indicating that the range of *E. coli* concentrations of surface water in baseline conditions largely falls within the larger range of concentrations exhibited in storm conditions, and that the differences between them may not be statistically significant. This suggests that point sources likely contribute more *E. coli* in storm conditions and non-point sources likely contribute more in baseline conditions.

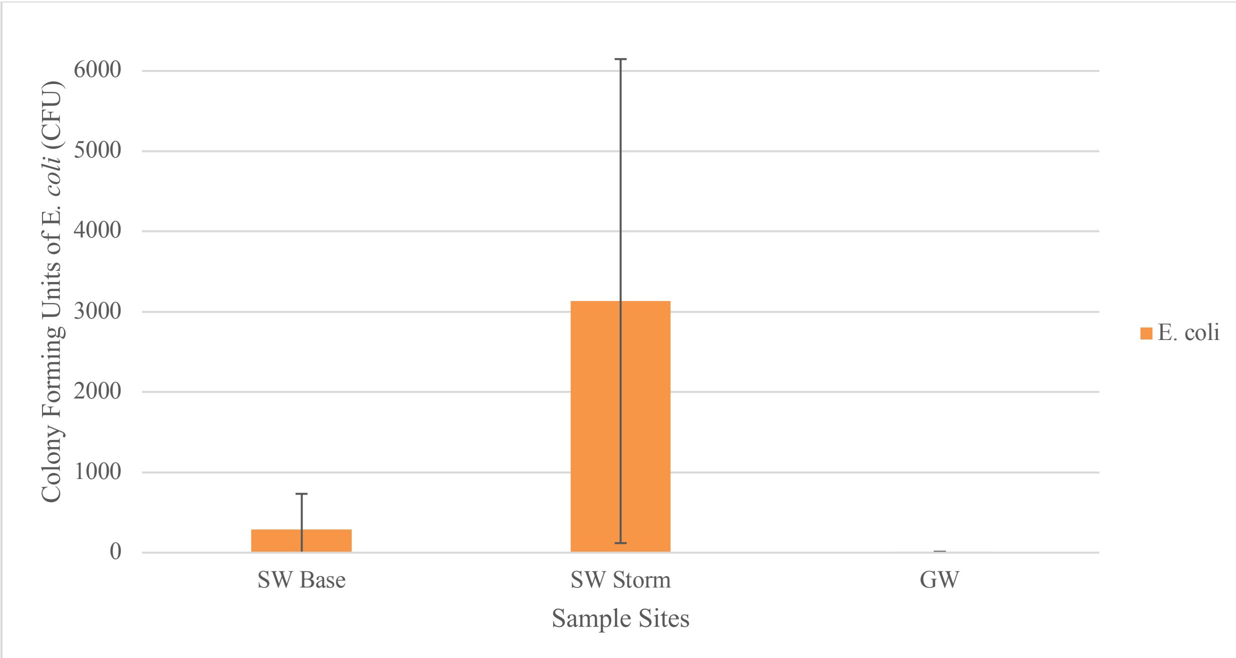

Figure 28: Mean aggregate *Enterococcus* concentrations (CFU) across corresponding dates and sampling locations for SW baseline, SW storm, and GW control samples collected from sampling locations in Nags Head, NC in October 2018. Error bars represent one standard deviation from the mean.

Observed bacteria data follows Mallin et al. (2013) trends as samples display high variability and have a positive correlation with rainfall events. *Enterococcus* averages observed by Mallin et al. (2013) range from 90 to 596 CFU/100 mL whereas this study found extraordinarily higher counts ranging from 1,459 to 8,164 CFU/100 mL (Figure 23). These differences can be attributed to differences in sample timing, as our study was limited to the month of October which follows the peak high-density tourist season where municipal water usage and wastewater amounts are highest. The large increase between baseline and storm averages for bacteria indicates contaminated runoff that can be attributed to human and/or animal sources, and similarly to nutrient discussion, more data are needed for broader conclusions.

Caffeine

Figure 29 shows the concentration of caffeine in water samples taken from the two GW control sites and two SW sites under baseline and storm conditions. Caffeine is often used as a tracer to link bacteria concentrations to anthropogenic sources as it is rare to find naturally in large concentrations, and can end up in waterways due to pollution from human waste. Caffeine could not be extracted from SW1 samples, and caffeine samples were not collected on October 27th, 2018 at SW3.

Trace amounts of caffeine were found in samples from all sites on all days for which caffeine was sampled, with the exception of October 26th, 2018 at GW2. However, an order of magnitude larger concentration of caffeine was detected in samples taken from SW2 under storm conditions on October 26th, 2018. This suggests that waters containing high concentrations of caffeine may have interacted with surface water under storm conditions at SW2, potentially linking caffeine-rich water sources, such as septic leachate, to the high mean aggregate nutrient and bacteria concentrations found at surface water sites, and particularly SW2, during and after the storm.

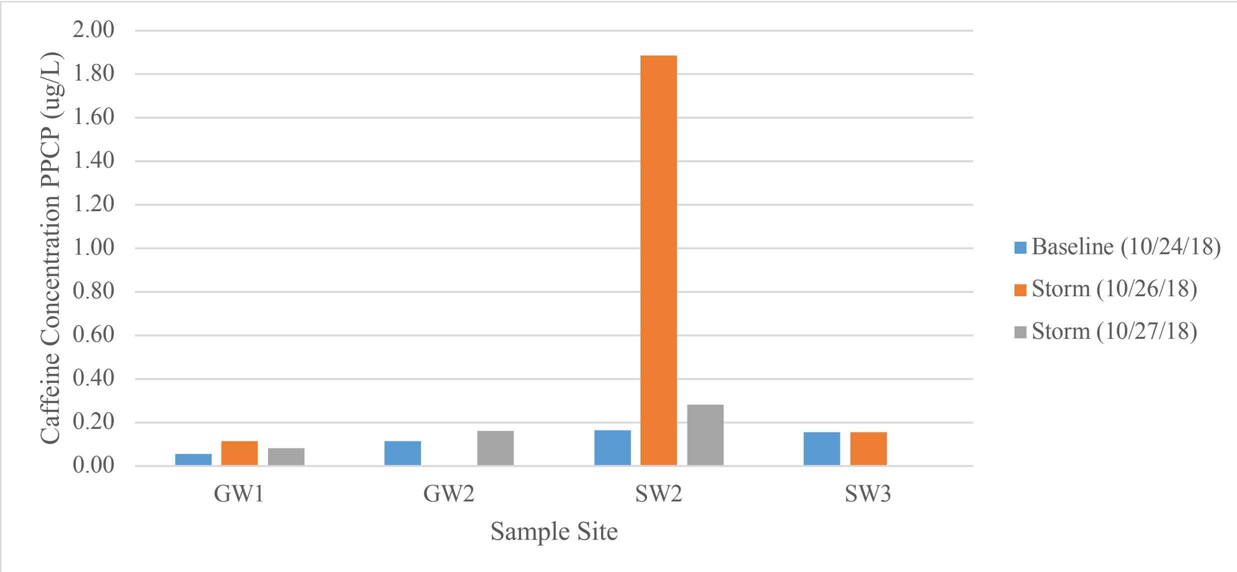

Figure 29: Caffeine concentrations (µg/L) during one baseline (absent of rainfall) sampling events and storm during and after a storm for samples collected from sampling locations in Nags Head, NC in October 2018.

Conclusions and Implications

Mean aggregate nutrient and bacteria concentrations found at each field sampling site largely correspond with the hypothesis that SW sites would exhibit higher nutrient and bacteria concentrations under storm conditions than during baseline conditions and GW control sites. For mean concentrations of all parameters, the standard deviations of SW storm, SW baseline, and GW samples were large, suggesting temporally variable contributions that may be the result of point sources. Interestingly, mean nutrient concentrations at SW sites closest to the ocean outfall were highest and decreased with distance from the OF, whereas the exact opposite was the case for mean bacteria concentrations at SW sites during and following the storm event, which were highest at the location farthest from the OF and decreased as distance to the ocean outfall decreased. This may be a result of bacteria feeding off of the nutrients as effluent flows from sites further inland to the ocean outfall during storm events, thus exhibiting an inverse relationship between nutrient and bacteria concentrations. These fluctuations in nutrient and bacteria concentrations were not reflected at the OF itself, which often exhibited comparably low concentrations of nutrients and bacteria in both storm and baseline conditions, likely as a result of effluent mixing with and being assimilated by ocean water upon leaving the outfall. This suggests mixing and dilution dissipates some water quality concerns in recreational ocean waters.

In addition to nutrient and bacteria analysis, preliminary caffeine analysis was conducted on all sampling sites except SW1 and the OF. Caffeine is frequently used as an indicator of GW and SW contamination by septic systems because it is present in a variety of products used by humans, such as coffee and personal care products, and is often present alongside bacteria and nutrients originating in human wastewater (Spence et al 2015). Trace amounts of caffeine were present at all sampling sites for which caffeine was tested under baseline conditions, and present in at least one of two storm samples for each tested site. Caffeine concentrations were found to be significantly higher at SW2 under storm conditions, strongly suggesting that nutrient and bacteria concentrations found in SW2 under storm conditions had been influenced by septic leachate. While this was only a preliminary analysis, Nags Head should consider more thoroughly sampling for caffeine in its SW and GW to better understand septic leachate interactions with these water reservoirs.

As can be seen in Figure 24 and Figure 27, *Enterococcus* and *E. coli* concentrations in SW samples under baseline conditions exceed EPA thresholds for these bacteria in recreational waters, with concentrations increasing significantly at SW sites during storm events. As storms increase in frequency and intensity and sea levels rise as a result of climate change, groundwater levels can be expected to rise as well (Lusk et al 2017). The saturation of soil from excess rainwater and GW level increase could lead both to more frequent flooding of Nags Head's residential areas and to widespread septic system compromise and failure, with unsafe levels of bacteria entering flooded streets from surface water drainage ditches influenced by septic leachate. While drainage ditches are not considered to be recreational waters by EPA standards, Nags Head should consider limiting the bacteria concentrations of its surface water drainage ditches as children have been known to play in flooded streets in Nags Head after storm events, creating the possibility for a significant public health issue to manifest.

Limitations

Time and logistical constraints have led to several important limitations of this study. Further, more comprehensive research is needed in order to continue investigating water quality and quantity parameters as they relate to environmental change and septic systems.

Primarily, the field data collected during this study was only representative for the month of October, which neglects any of the summer tourist season months, rendering our samples not entirely representative for either the on-season (generally April to September) or off-season (generally October to March). Further, the study utilized only three baseline sampling events and only one storm event, which does not represent accurately the ways in which storms affect water quality since this one storm event cannot be extrapolated to demonstrate the overall effects of storms. It is important to also acknowledge that we defined a storm event based on our qualitative observation rather than a quantification of specific thresholds or values. This hinders our ability to broadly apply our research, as we lack the quantitative specificity of what qualifies a storm. A limitation regarding the samples themselves is that there was no water present in two of our sampling locations on two different sampling days. SW1 and SW3 lacked water during the baseline sampling event on 10/25/18, while SW1 lacked water during the first sampling of the storm event on 10/26/18. As a result, we do not have fully comprehensive data to demonstrate comparisons at each site.

Another limitation involves the sampling locations. Our intention was for the groundwater well sampling locations to serve as control sites, yet given the quantities of nitrate found within GW2, it is unclear how effective of a control these locations are. The location of this groundwater well was adjacent to an impervious surface, a road in a residential neighborhood, which may have affected the nutrient content in the well. This high concentration skewed aggregate nitrate concentrations for both groundwater controls, challenging our ability to use these sites as control variables, particularly for nutrients such as nitrate. This study cannot be extrapolated to represent the entirety of the Outer Banks, as it is indicative only of changes to the

Gallery Row sub-watershed in Nags Head. Therefore, more sampling sites from a larger spatial area would be beneficial to better understand interactions across the barrier island landscape.

The historical dataset we used in comparison with our field sampling was inconsistent in its sampling, such that it is unclear whether or not these historical samples occurred in any correlation with rainfall events. It is therefore difficult to use them comparatively with our study, as we distinguished between baseline and storm events.

Further, our attempt to understand direct tracers of septic effluent through the use of caffeine analysis, while informative and indicative of human presence, could have been made stronger and more correlative. Our analysis excluded caffeine analysis for the outfall sample and SW1 due to logistical constraints, hindering any further conclusions to be drawn if this data had been obtained. Tracing multiple indicators, such as detergents or pharmaceuticals and personal care products, may strengthen future studies. One factor that our study failed to consider was the possibility that the presence of caffeine in our samples could be attributed to the presence of the southeastern U.S. plant species *Ilex vomitoria* or yaupon holly, as caffeine is naturally present in this plant (Peeler et al., 2006). While we do not know whether this plant contributed to the presence of caffeine in our samples, it is still possible and should be accounted for in any further research.

Generally, we acknowledge that the statistical significance of our study is reduced due to the lack of more comprehensive statistics on a large dataset, since our working dataset was limited. Given this limitation, we extrapolated only a fraction of what is possible to be understood regarding the effects of septic systems on environmental quality, such that future studies are encouraged to sample in greater frequency, across the landscape.

Conclusions

Our study focused on how water quality and quantity in the town of Nags Head is being affected by a combination of shifting hydrologic factors and anthropogenic stressors as well as how property owners perceive changing environmental conditions.

Our historical water level analysis showed that water level fluctuated, as expected, with precipitation across all sampling locations. We were surprised that we did not see an increase in water level in the summer, corresponding to increasing water use associated fluxes of water from the confined drinking water aquifer to the groundwater aquifer. Most importantly, we also determined that the water level exceeded the depth that would keep it sufficiently separated from the depth of septic drainfields to allow for the recommended amount of percolation through unsaturated soils and natural treatment for contaminant removal on 49% of sampling occasions. This is especially concerning since the overall trend in the data is that water level has increased over time, and although our dataset is shorter than that required to attribute the increase in water level to sea level rise, we expect sea level rise will continue to increase the water level of this coastal town. This rise in sea level will also raise the GW table in an unknown way across the landscape, which will further shrink the separation between groundwater and septic drainfields, thereby posing increasing risks to water quality. The comparison of GW levels to depth of septic drainfields and patterns over time, following storm events, and across the landscape warrant further study.

Our water quality field study findings indicate that precipitation events are positively correlated with spikes in the surface-water concentrations of nutrients like ammonia and nitrate-nitrogen as well as with massive spikes in *Enterococcus* and *E. coli* cell counts. While we cannot definitively state that the increased levels of nutrients and bacteria present in the surface-water are directly due to septic system leachate because of our low sample size and the great degree of variability within our dataset, septic systems are still a very probable contributor to surface-water quality degradation, especially considering the historical water level findings regarding inadequate separation between septic drainfields and GW levels across Nags Head. While our original hypothesis that stormwater and precipitation events would cause greater interactions between septic system leachate and surface-water reservoirs is likely supported by a spike in caffeine concentrations at the one SW location for which we have multiple caffeine measurements, the variation in our baseline nutrient and bacteria data suggests contributions by some type of temporally variable point source pollution – possibly animal waste, fertilizer, or even a single particularly leaky septic system – that makes it difficult to attribute background and high nutrient and bacteria concentrations to a consistent groundwater-septic interaction. Although we lack the recommended 30-year tidal gauge record necessary to know if the minor decreases in the depth to the groundwater is due to SLR, our analysis of historical data revealed that the groundwater table is consistently close enough to the surface to interact with septic drain fields. As sea-levels continue to rise due to thermal expansion and melting ice sheets, we expect that the groundwater table will rise with it and the Town of Nags Head will experience septic leachate interacting with GW before being properly treated and septic system failures with increasing frequency.

Analysis of our semi-structured interviews revealed that participants are attached to the waters of Nags Head for a myriad of reasons including aesthetic value and uniqueness, as well as for tangible benefits like recreation. Many of them believed that not only were the waters and other environmental conditions changing, the changes were being exacerbated by a combination of poorly managed stormwater and tourist-driven economic development that is resulting in increased flooding and decreased water quality. While many participants mentioned a broad variety of flood mitigation methods, they expressed a shared sentiment that there 'was only so much that one can do' to mitigate flooding. They lacked a reliable source of information about septic system maintenance, methods of wastewater treatment beyond septic, and quantitative measures of water quality. In general, septic systems as a wastewater treatment method were preferred over centralized sewage for a number of reasons including concerns about the expense and feasibility of installation and maintenance.

After analyzing our interviews, it seems that the citizens of Nags Head could benefit greatly from a central repository of information on wastewater treatment, flooding incidence and water quality that could better prepare the public for future flooding events and increasing climatic variability. A lot of participants acknowledged that they were in Nags Head because of the water, but on the other hand were reluctant to spend money on fixing the problems of flooding and water quality. Existing efforts like the Septic Health Initiative currently managed by the Town of Nags Head are a step in the right direction, but they do not seem to be effectively communicating that flooding and water quality problems are ones that the townspeople are going to have to make decisions about very soon and that the decisions will not be without cost.

If this study were to continue, future researchers would be wise to amass a spatially extensive and temporally consistent dataset to capture the variability in Nags Head water quality and depth to groundwater by employing finer resolution spatial sampling along a hydrological gradient. While the 'control' groundwater wells used in our study were not affected by storm events, a new well – free of nitrate nitrogen – should be found to replace GW2 as a control, and the control wells should be tested for nutrients and bacteria early to make sure they are sufficiently untainted. Particular attention should be paid to the effects of heightened water usage during the summer tourism season in Nags Head, as well as the unique 'Nor'easter' storms in winter.

If global trends of rising sea-levels and increasingly erratic and extreme storm events continue as predicted by the most recent Intergovernmental Panel on Climate Change report, then the Town of Nags Head and other coastal communities similar to it will see ever more frequent interactions between rising groundwater tables, stormwater, and septic leachate resulting in the continued deterioration of water quality in surface and groundwater reservoirs. Future decision makers will need a quantitative understanding of the interactions between water fluxes and septic system leachate in order to craft policies that bolster the resilience of coastal communities to changing environmental conditions.

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Appendices

APPENDIX A

OBXFS 2018 Capstone Interview Guide
v. 2018 October 3

Materials
Consent document
iPad (Remember to check battery life)
Charger
Pen/pencil
Clipboard

Introduction:
Go over topic of interview and project; give brief summary of what we're doing.

- Summary: We are conducting interviews with a variety of people around the Gallery Row watershed about perceptions about coastal waters, flooding, wastewater, and changing environmental conditions in Nags Head.

Ask the participant to read and review the consent document. Make sure s/he doesn't have any questions.

Ask if recording is alright; explain the importance of having a recording if they are skeptical.

- Importance: It helps us to better keep track of information and hear what you have to say rather than constantly taking notes. The other students and I are the only ones who will hear the recordings and they will be deleted at the end of the project.

To start the recording, ask him/her to mark the recording by saying a few sentences, like his/her name, the date and where you are. Watch the levels to make sure you are recording at a good level. [Instructions for the Voice Recorder Pro app are at the end of this guide.]

Section 1:
I'd like to start by asking you to tell me a little about your history in Nags Head.

How long have you been living in Nags Head?

- What brought you here?
- If not a life-long resident: Had you lived in a coastal place previously?
    - Y: Where was that?
    - N: When you moved, did you specifically want to be at the coast? Why was that?

How, if at all, did your [property's/home's] proximity to the water factor into why you chose it?

- What about it attracted you to it?

Here in Nags Head we're surrounded by water. How do the ocean and sound waters matter to you?

- If you need to clarify: How are the ocean and sound important to you? or What do they mean to you?
- What roles do these waterbodies play in your life?
    - Prompt: How do they affect your livelihood?
    - Prompt: How do they affect your health? Your mood?
- What roles do you think these waters play in the life of the town?

How often do you go out to the ocean?

- What about the soundside?
- What do you do while you're there?

How are these waters important for your sense of your identity? And by identity I mean the ideas, relationships, spaces, and sense of belonging – that shape who we are, where we belong, the community we're a part of.

<u>Section 2:</u>
Now I'd like to continue talking about the ocean and water with you, but I also want to ask you about possible changes in the health of the area that you may have noticed.

How would you describe the ocean's health, in general, in the Nags Head area?

Follow-up:

- If s/he gives a generally positive description: Do you have any concerns about water quality in the ocean?
    - What specifically concerns you?
    - For each concern: How do you think that has come about?
- If s/he gives a poorer assessment: What do you think could be contributing to that?
    - If s/he hasn't specifically mentioned water quality: Do you have any concerns about water quality?
    - What specifically concerns you?
    - For each concern: How do you think that has come about?

Thinking beyond the ocean or sound, can you describe any environmental conditions that you've noticed have changed around Nags Head?

- Prompts: precipitation patterns (storm frequency, storm intensity, rainfall amounts), air or water temperature, erosion rates, water/tide level, landscape/vegetation

In terms of your neighborhood, how has that area been affected by storms since you've lived there?

Follow-up:

- How much of a concern is flooding for you personally?
- What is a typical flooding event like for your property and around your neighborhood?

- Could you describe the most impactful flooding event that you have experienced since coming to this neighborhood?

What sorts of preventative measures do you take, if any, to reduce the impacts of flooding on your [property/home/business]?

What sorts of preventative measures have you noticed your neighbors, friends, or other community members taking to reduce the impacts of flooding?

How much do you think that flooding is a normal part of living in Nags Head?

- Would you say that has always been true?
- Has flooding changed in any way over time?
- If s/he is not native to the area: How well did you understand the risks of flooding when you moved to Nags Head?

<u>Section 3:</u>
Now that we've talked about surface-water and stormwater flooding, I'd like to ask you about wastewater. And when I say wastewater I'm talking about water that has been used in homes and businesses and then released down different kinds of drains.

How familiar would you say you are with the ways wastewater is treated in Nags Head?

Is your [home's/business's] wastewater treated on-site in a septic tank system?

- What do you do to maintain your septic tank system?
- Where did you get your information about what to do to maintain it?
- Have you ever had any issues with your septic tank system?
- What concerns if any do you have about your septic tank system?

Some sections of Nags Head have package plants for wastewater treatment instead of individual on-site septic tank systems. Have you heard anything about that?

- What do you think about that as an alternative to septic tank systems?
- What would you think if that sort of more centralized wastewater treatment became more widespread in Nags Head?
- How much of chance do you think there is that a centralized sewage system might happen in Nags Head?

As far as you know, how does how the town is planning for and managing wastewater into the future align with your own thinking about how to address wastewater in the future?

Do you feel like you and other local residents can influence wastewater management in Nags Head?

- If yes: In what ways?

<u>Section 4:</u>

So we've talked about water quality and water quantity, and we've talked about surface-waters and wastewater. Who would you say should be responsible for managing water quality and quantity?

- What do you feel you as an individual can do about it?
- What can the community do?
- What suggestions do you have for how to address water quality and quantity issues in Nags Head?

How open to adapting to changing conditions would you say the Nags Head community is?

- If s/he says Not that open: How could local adaptability be increased?
- If s/he says Open: In what ways do you think they are?
    - What factors might prevent adaptations from being implemented?

<u>Closing Questions:</u>
That's everything that I wanted to ask you. Is there anything you'd like to add about water, flooding, wastewater or anything else that we haven't discussed?

Do you have any questions for me?

<u>Conclusion:</u>
Thank you so much for participating in this interview. I'd like to reiterate that all of your responses will be kept completely confidential, and that if at any time you have any questions about this interview or our project, you can feel free to contact me or our project coordinator. Provide contact info if requested and/or s/he can keep the consent document if s/he wishes. You've been incredibly helpful, and I appreciate you giving us your time and insights.

Do you know of anyone else you think would be a good person for us to interview?

- Ask for contact information to go along with names.
- Clarify that they should not take it upon themselves to ask people to do interviews. If they ask about contacting the person first, explain that they can reach out to the person and ask if they would be willing to hear from a student about the project and then think about participating.

Thanks again for participating in this study. We will be compiling the findings of our study into a report and giving a public presentation about them at the end of the semester. You are more than welcome to attend. It will be Thursday, December 13 from 2:00-4:00pm at the Coastal Studies Institute.

APPENDIX B

Hydrology Field Sampling Protocol

Field supply list

- 6 Pre-labeled sampling bottles (acid-washed for nutrient analysis and autoclaved/sterile for bacterial analysis)
- 2 extra sampling bottles
- Sharpie
- Label tape
- Extra ziplocks
- Pikstik
- Waders
- Towels
- Bailers*
- Twine
- Scissors
- Small cooler for outfall sample transfer with ice*
- Bucket for outfall and groundwater sample environmental measurements
- Large cooler with ice
- Hand sanitizer
- First aid kit
- Technu
- Sunscreen
- Bug spray
- Deionized water rinse/squirt bottle
- Kimwipes in ziplock
- YSI 85
- Water level gauge/meter (name?)
- GPS
- Latex gloves
- Notebook
- Writing instrument
- Dress appropriately for sites (ocean, closed toed shoes (cactus, poison ivy), etc.)
- Yard stick

Sampling locations

- GW1 – Well behind split rail fence at intersection of Roanoke Trail and Nags Head Woods Road, in the Nags Head Woods. Remove outer well cap and inner cap and be sure to replace both caps when finished sampling
  N 35.99035 W 075.66731
- GW2 – Well in blue box at the base of Jockey's Ridge, at the end of Lookout St. (158 north past Jockey's Ridge, left at Windjammer into North Ridge neighborhood, right onto Lookout) – lock combo (38, 24, 10 – turn dial on lock right 3 times and stop at 1st number; turn left past 1st number and on next turn, stop on 2nd number; turn right and stop on 3rd number)

N 35.96626 W 075.63715(this is not in our watershed, but is the highest elevation well – a true control)

- SW1 – Surface-water ditch on S. Memorial Avenue near the north side of the intersection with E. Barnes St. in Nags Head
  N 35.98202 W 075.63947
- SW2 – Surface-water ditch on S. Memorial Avenue near the north side of the intersection with E. Abalone St. in Nags Head
  N 35.98802 W 075.64304
- SW3 Surface-water ditch on the south side of Red Drum, running perpendicular to S. Virginia Trail/Hwy 12/Beach Road – be sure to fully pull off of 12 and its bike lane when sampling
  N 35.98823 W 075.64204
- Gallery Row Ocean Outfall – on the ocean beach, just south of the E. Gallery Row beach access – park on the side of the road, NOT in the sand unless you are in a 4-wheel drive vehicle
  N 35.98886 W 075.64031

Sample collection dates/times
Baseline samples

- October 5, 2018
- October 24, 2018
- November 6 or 7, 2018

Storm samples
3 time points throughout storm

Sample collection protocol
It is very important to use aseptic technique for all aspects of bacterial sample collection and processing! This means that you should avoid sample bottles and bailers coming in contact with anything (hands, ground, water other than sample water) aside from the samples!

Do not let the GPS or YSI handheld screen get wet!

At each sampling location:

- Double-check that you are at the correct location via visual markers and GPS
- Record observations about the study site, weather, date, time, movement of water, etc.

At surface-water sampling sites:

- Record environmental measurements using YSI

  <u>YSI User Manual</u>

    - Calibrate for DO (See pg. 14 of YSI User Manual)
        - Use the 'Mode' button to swap to measuring DO – The units will be mg/L or % - then press both the 'up' and 'down' arrow keys at the same time. The machine will ask for elevation to the nearest 100 ft, so leave it on 0 and press 'enter'. The machine will then begin calibrating – let it stabilize until the readout on the screen stops fluctuating. Once it's stable press the 'enter' key. The device is now calibrated for DO.

    - Measure DO (mg/L), salinity (ppt), temperature (C), and conductivity (us) – make sure that the top and bottom of the probe are immersed in the water (you may have to hold it sideways away from the bottom)
    - Rinse the YSI with DI water and wipe with a kimwipe after each measurement!
- Collect samples (if you have disturbed sediment making YSI measurements, make sure to choose a sample collection location upstream of the disturbance-if you have to step into a ditch, for example, try not to disturb the water)
    - Uncap the sample bottle (be sure not to touch the inside of the cap or bottle)
    - Use Pikstik to hold bottle and collect sample from just below the surface of the water – try not to touch the bottom and resuspend sediment
    - Recap the bottle without touching the inside of the lid or mouth of the bottle
    - Immediately place on ice, in the dark

At outfall sampling site:

- Record environmental measurements using YSI
    - Collect measurements based on the direction of the waves/longshore current: if the waves are coming in South, sample on that side of the outfall, vice versa
    - Collect a bucket of water from the surf zone
    - Calibrate YSI for DO
    - Measure DO (mg/L), salinity (ppt), temperature (C), and conductivity (us) of water sample collected in bucket – make sure that the top and bottom of the probe are immersed in the water (you may have to hold it sideways away from the bottom)
    - Rinse the YSI with DI water and wipe with a kimwipe after each measurement!
- Collect sample from the surf zone
    - Uncap the sample bottle and have someone on shore hold it (be sure not to touch the inside of the cap or bottle)
    - Collect sample from the surf zone
    - Recap the bottle without touching the inside of the lid or mouth of the bottle
    - Immediately place on ice, in the dark in the small cooler and transfer to the large cooler when you arrive back at the car

At groundwater sampling sites:

- Collect water from the well using a bailer
    - Unwrap the bailer and be sure not to touch the ground or anything else with it. Use latex gloves to avoid contamination
- Bail 2-3 gallons of water out of the well (half a bucket) and dispose of away from the well
- Bail 4 more times into the bucket for environmental measurements
- Record environmental measurements using YSI
    - Calibrate YSI for DO
    - Measure DO (mg/L), salinity (ppt), temperature (C), and conductivity (us) of water sample collected in bucket – make sure that the top and bottom of the probe are immersed in the water (you may have to hold it sideways away from the bottom)
    - Rinse the YSI with DI water and wipe with a kimwipe after each measurement!

- Collect sample using the bailer
    - Uncap the sample bottle (be sure not to touch the inside of the cap or bottle)
    - Collect sample using the bailer
    - Recap the bottle without touching the inside of the lid or mouth of the bottle
    - Immediately place on ice, in the dark

Transport samples back to the lab and process samples ASAP

APPENDIX C: Water Quality Field Study Laboratory Sample Processing and Analysis Protocol: IDEXX procedure for total coliform, E. coli, and Enterococcus bacterial samples

It is very important to use aseptic technique for all aspects of bacterial sample collection and processing!

1. Plug in Qunti Tray sealer (when the light is green, it is ready to use)
2. Remove shrink wrap from sterile 100ml vessels to be used for analysis – 2 per water sample- labeled accordingly (enter vs coli, date, time, OBXFS)
3. Measure 90ml of autoclave water into graduated cylinder and transfer to each empty 100ml vessels
4. For each water sample, process 2 replicates of each the Colilert and Enterolert tests
    a. Snap open Colilert/Enterolert media packets and pour into vessel containing 90ml of sterile water (ensure all of the media was poured out, sometimes it helps to tap them all upside down before they are opened to loosen the media inside the packet)
    b. Add 10ml of water sample to vessel containing 90ml of sterile water and Colilert/Enterolert using 10ml pipette. Change tip with each different water sample.
    c. Close cap and agitate, let rest. Repeat until all of the media has dissolved.
    d. Pour contents of vessel with water, media and sample into a QuantiTray 2000.
    e. Place Quanti Tray into molded rubber mat and insert into the Quanti Sealer. Remember to keep the tray upright because if the top is not closed you could potentially spill it all over the place (Figure 1.)
    f. Remove sealed Quanti Trays and place into appropriate incubator (Colilert - 35°C±0.5°C ; Enterolert - 41°C ± 0.5°C)
5. Incubate for 24 hours
6. After incubation, remove Quanti Trays and count large and small positive wells using a blacklight (for some) and record on data sheet.
    a. Enterolert positive glow blue
    b. Colilert positive
        i. E. coli glow blue
        ii. Total Coliforms turn yellow
7. Use IDEXX Most Probable Number (MPN) data sheet to determine MPN of colony forming units (CFU) of bacteria per 100ml of sample. Remember to move the decimal over 1 place to the right because of your dilution. The data sheet gives results for 100ml of sample, you used 10ml.

Filtration for nutrient samples

- To avoid nutrient contamination between samples, be sure to rinse the filter box and towers and transfer vessels with deionized water (3x) after any of these things had come in contact with a sample.
- To avoid dilution of nutrient samples by rinse water, rinse the manifold components and falcon tube with sample if there is any deionized water present after rinsing.
- Be sure to invert samples immediately before pouring them into the filtration towers to make sure that the sample is well-mixed.

1. Set-up filtration manifold
    a. Box connected to filter via tubing; filter connected to vacuum pump via tubing

b. Label falcon bottles with your sample names, dates, times (for storm samples) and OBXFS and place in foam of filter box to space such that the filtrate dispensers are inside of the tubes when the filtration box top is put in place. Do not touch inside of the tubes.
c. Place top on filtration box.
d. Place pre-combusted Whatman GF/F filters onto the filtration manifold. Place filtration towers on top of the filters, making sure that they are seated/sealed properly (they should be straight and not wobbly).
e. Invert water samples and immediately pour the appropriate amount into the corresponding filter towers
    i. You need at least 30 mL of filtrate
    ii. For samples with a lot of sediment and/or algae, filter small volumes at a time, changing out filters in between by removing the entire box top with the filtration towers attached

2. Turn on vacuum pump (not above pressure of 15 mmHg)
3. When filtration has been completed and you have at least 30 ml of sample in the falcon tubes, remove the towers and filtration box top and rinse with deionized water. Remove falcon tubes containing samples and cap.
4. Transfer samples to a Ziplock with the date, "OBXFS", time (if a storm sample), and "nutrients" and place in the freezer. Be sure to add the samples to the sample log on the outside of the freezer.
5. These samples will be analyzed for dissolved nutrients using a Lachat Quickchem in November.

*some sample will finish filtering before others. When the samples finish filtering, close the prongs of the values so that the rest of the samples can retain the pressure. UP/DOWN prongs=open, sideways=closed

APPENDIX D: Historical water level figures for the OBXFS 2018 Capstone research project investigating water level trends across the landscape of Nags Head, NC from 2011 to 2017.

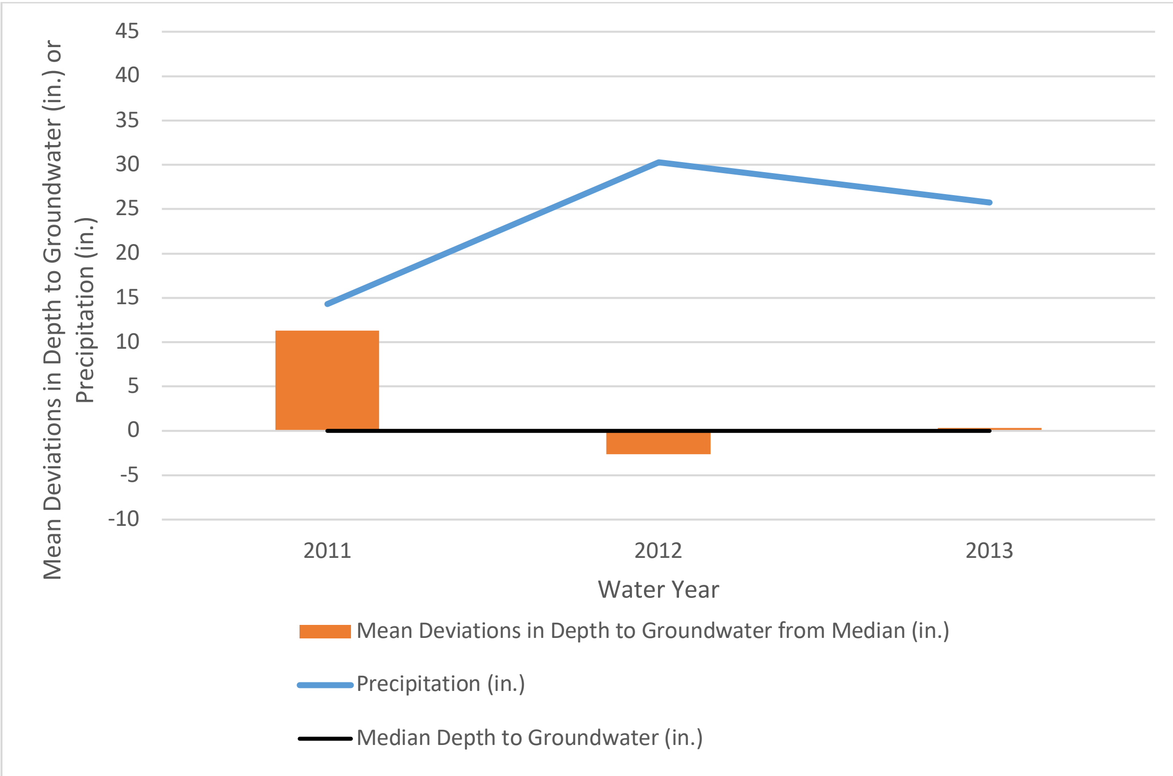

Figure 1. Depth to groundwater at the Blackman Street groundwater well, Nags Head, NC from 2011-2013 expressed as mean deviations in depth to groundwater from the median for each water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums. The mean depth to groundwater relative to the 2011-2013 median alternates from positive (indicating that water level is further from the ground surface) to negative (indicating that water level is closer to the ground surface) annually. However, the dataset for the Blackman Street well was limited in duration.

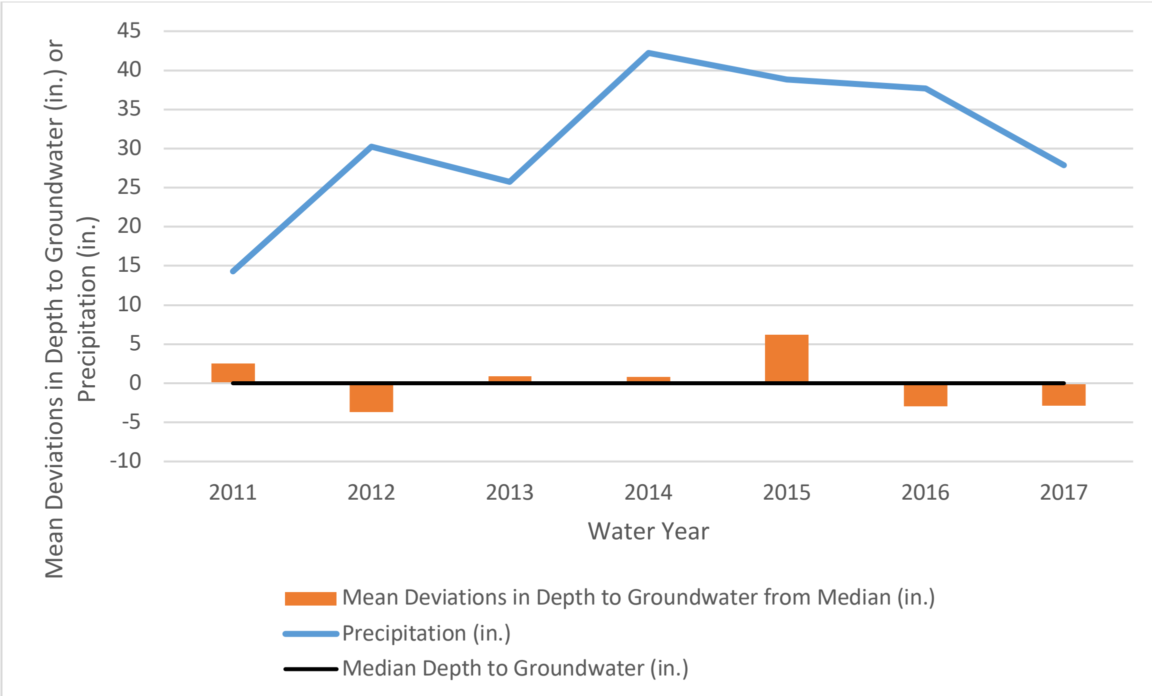

Figure 2. Depth to groundwater at the Juncos #1 groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in depth to groundwater from the median for each water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums.

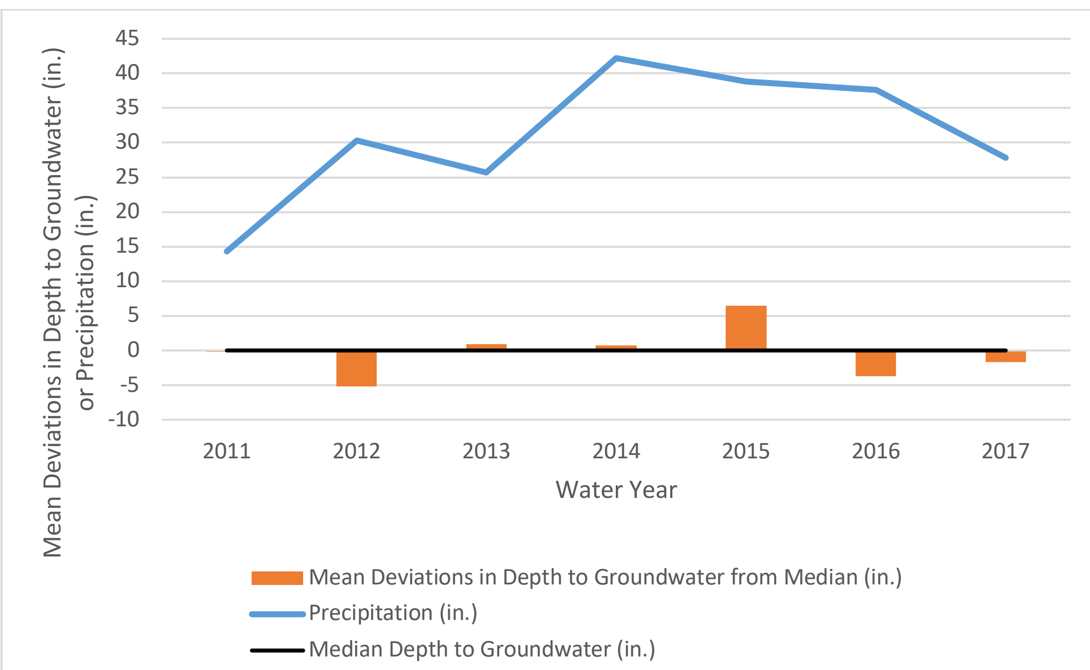

Figure 3. Depth to groundwater at the Juncos #2 groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in depth to groundwater from the median for each water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums.

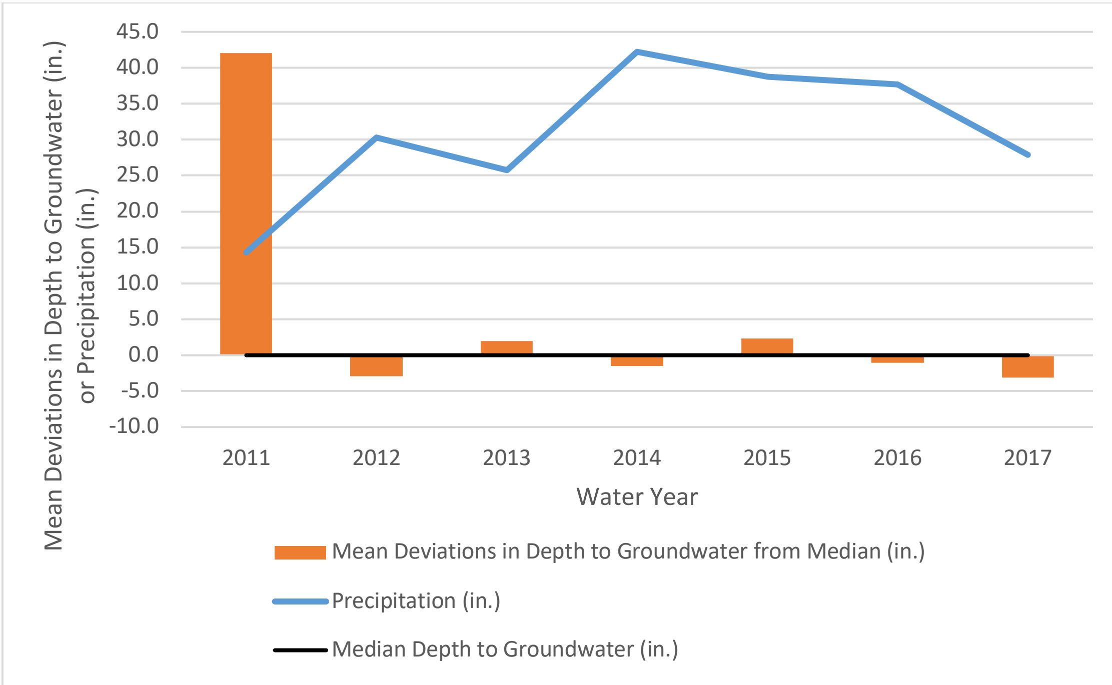

Figure 4. Depth to groundwater at the Nags Head Control groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in depth to groundwater from the median for each water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums. The mean depth to groundwater relative to the 2011-2017 median alternates from positive (indicating that water level is further from the ground surface) to negative (indicating that water level is closer to the ground surface) annually. Depth to groundwater has an inverse relationship with the sum of annual precipitation.

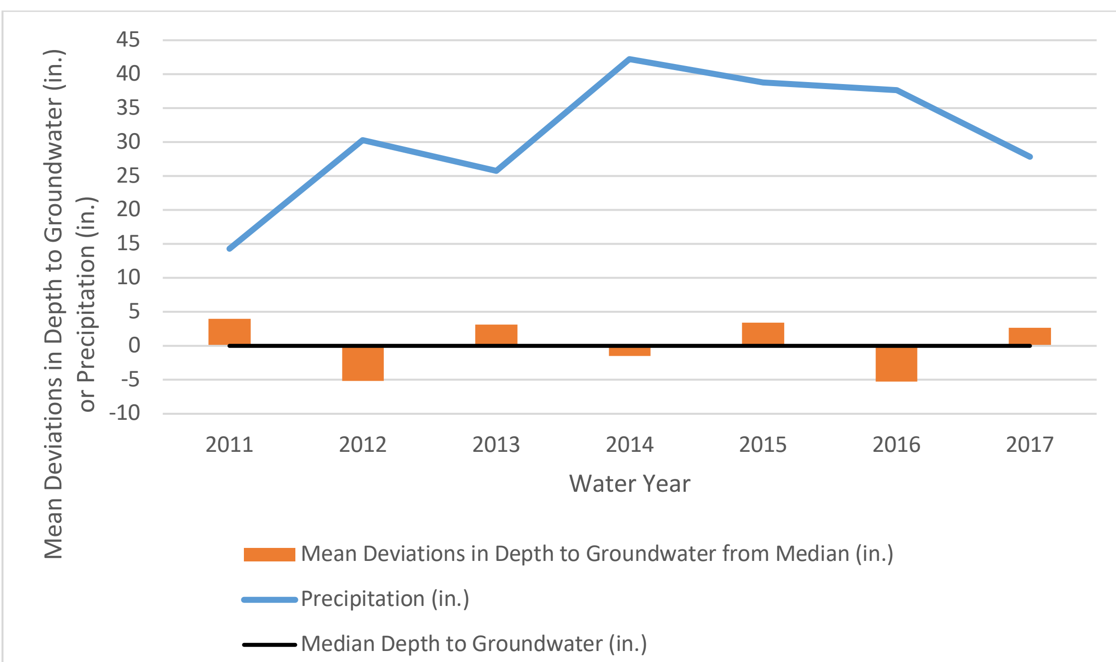

Figure 5. Depth to groundwater at the Nags Head Fire Station groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in depth to groundwater from the median for each

water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums. The mean depth to groundwater relative to the 2011-2017 median alternates from positive (indicating that water level is further from the ground surface) to negative (indicating that water level is closer to the ground surface) annually. Depth to groundwater has an inverse relationship with the sum of annual precipitation.

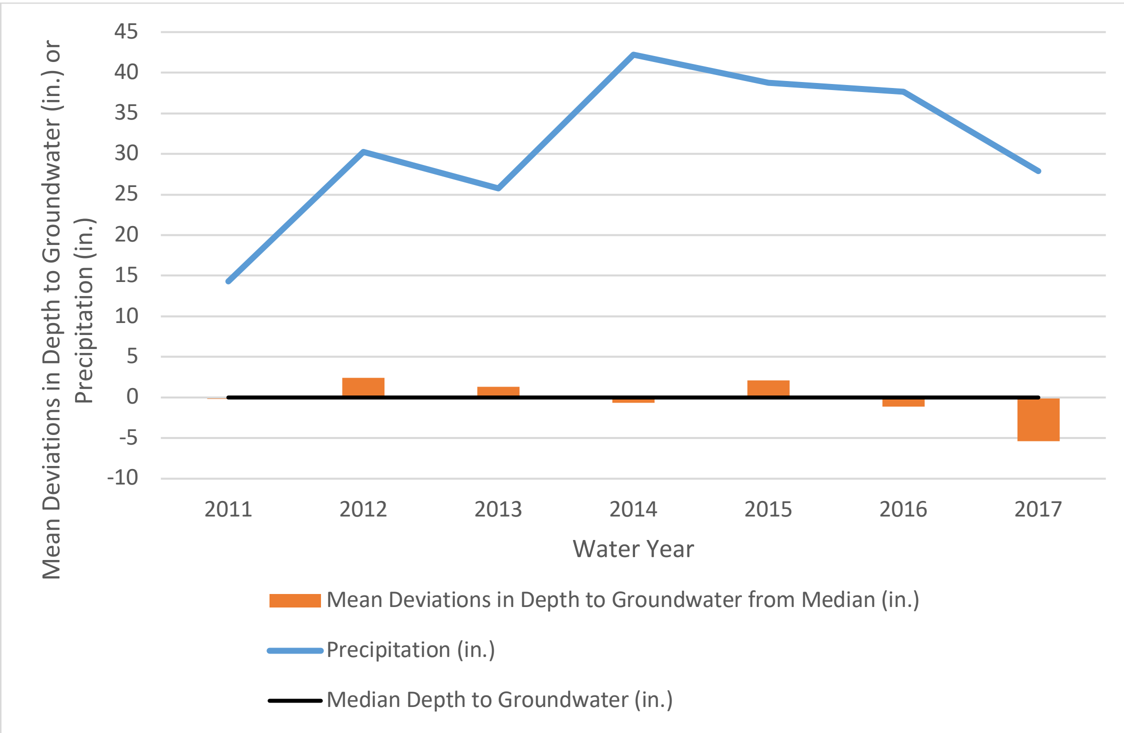

Figure 6. Depth to groundwater at the Old Cove #1 groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in depth to groundwater from the median for each water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums.

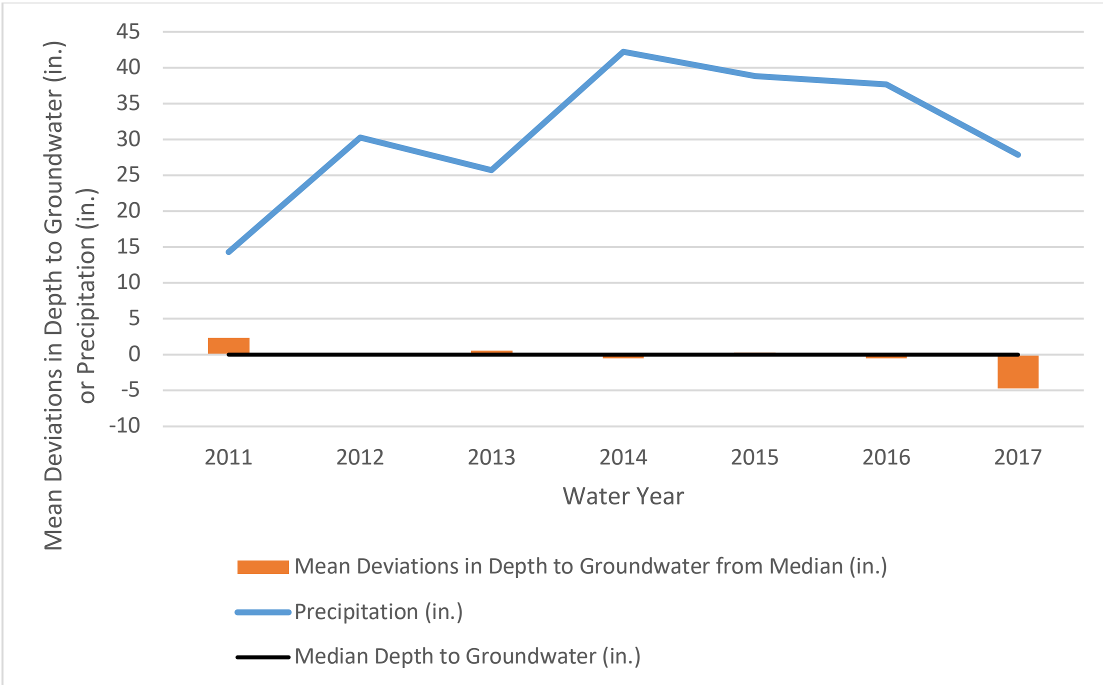

Figure 7. Depth to groundwater at the Old Cove #2 groundwater well, Nags Head, NC from 2011-2017 expressed as mean deviations in depth to groundwater from the median for each water year. The median serves as a baseline to compare depth to groundwater for each water year and annual precipitation sums.

APPENDIX E: Summary statistics for changes in depth to groundwater for spring, summer, and fall for these subw-atersheds: Drainage Basin 1, Drainage Basin 2, Drainage Basin 32, Nags Head Control, Drainage Basin 16, and Drainage Basin 8.

Water Year	**Changes in Depth to Groundwater**														
	Spring (March - May)					**Summer (June - August)**					**Fall (September - November)**				
	Count	**Mean**	**Max**	**Min**	**StdDev**	**Count**	**Mean**	**Max**	**Min**	**StdDev**	**Count**	**Mean**	**Max**	**Min**	**StdDev**
							Drainage Basin 1								
2011	3	29.60	36.00	24.00	6.04	1	48.00	48.00	48.00	N/A	1	35.00	35.00	35.00	N/A
2012	3	28.00	33.00	21.00	6.24	2	12.00	16.00	8.00	5.66	2	23.50	24.00	23.00	0.71
2013	2	24.25	24.50	24.00	0.35						3	25.17	27.00	24.00	1.61
2014															
2015															
2016															
2017															
							Drainage Basin 2								
2011	3	38.80	51.60	32.40	11.09	2	50.50	52.00	49.00	2.12	1	38.00	38.00	38.00	N/A
2012	3	30.00	37.00	23.00	7.00	2	14.00	15.00	13.00	1.41	2	24.50	25.00	24.00	0.71
2013	2	29.25	30.00	28.50	1.06	4	32.38	47.00	21.00	10.78	4	30.88	34.00	28.50	2.32
2014	3	20.33	25.00	17.00	4.16	6	31.33	38.00	24.00	5.50	1	28.00	28.00	28.00	N/A
2015	3	28.00	33.00	21.00	6.24	6	35.92	42.50	28.00	5.46	3	32.67	37.00	25.00	6.66
2016	5	26.00	32.00	23.00	3.92	5	27.10	36.00	22.00	5.84	3	28.33	33.00	24.00	4.51
2017	3	33.67	38.00	29.00	4.51	4	32.25	34.00	31.00	1.50	1	16.00	16.00	16.00	N/A

Drainage Basin 32

2011	3	16.00	18.00	12.00	3.46	2	21.75	27.50	16.00	8.13	1	16.00	16.00	16.00	N/A
2012	3	9.33	10.50	8.50	1.04	2	12.00	13.50	10.50	2.12	2	17.00	17.00	17.00	0.00
2013	2	10.00	12.00	8.00	2.83	4	20.25	26.50	15.00	4.77	4	17.75	22.00	8.00	6.55
2014	3	17.42	22.00	13.25	4.39	6	19.13	24.00	15.50	3.37	1	15.50	15.50	15.50	N/A
2015	3	18.17	22.00	10.75	6.42	6	27.42	32.00	24.50	2.82	3	19.25	20.25	18.50	0.90
2016	5	11.75	16.25	8.75	2.84	5	14.65	23.25	10.50	5.30	3	14.25	18.00	9.50	4.34
2017	3	13.17	15.00	11.00	2.02	4	16.94	19.50	15.25	1.81	1	8.50	8.50	8.50	N/A

Nags Head Control

2011	3	144.80	150.00	140.40	4.85	2	77.50	84.00	71.00	9.19	1	69.00	69.00	69.00	N/A
2012	3	63.83	67.00	62.00	2.75	2	57.00	58.00	56.00	1.41	2	59.00	62.00	56.00	4.24
2013	2	59.50	60.00	59.00	0.71	4	68.50	70.00	67.00	1.73	4	64.25	71.00	60.00	4.72
2014	3	58.67	61.00	57.00	2.08	6	62.50	67.00	58.00	3.39	1	65.00	65.00	65.00	N/A
2015	3	59.83	62.50	56.00	3.40	6	66.25	69.00	61.00	2.89	3	69.00	72.00	64.00	4.36
2016	5	59.00	61.50	56.00	2.03	5	63.42	69.00	58.00	4.13	3	64.33	65.00	64.00	0.58
2017	3	59.50	61.00	57.50	1.80	4	63.25	65.00	61.00	1.71	1	48.00	48.00	48.00	N/A

Drainage Basin 16

2011	3	102.00	115.20	84.00	16.14	2	90.50	92.00	89.00	2.12	1	96.00	96.00	96.00	N/A
2012	3	101.67	105.00	96.00	4.93	2	58.50	63.00	54.00	6.36	2	93.00	94.00	92.00	1.41
2013	2	101.00	103.00	99.00	2.83	4	84.25	91.00	75.00	7.27	4	103.00	108.00	99.00	3.74
2014	3	89.50	91.50	86.00	3.04	6	87.08	93.00	80.00	5.61	1	101.00	101.00	101.00	N/A
2015	3	91.00	97.00	84.00	6.56	6	94.75	104.00	87.00	7.45	3	101.00	105.00	96.00	4.58
2016	5	92.30	99.00	81.00	8.07	5	77.40	82.00	73.50	4.08	3	93.00	100.00	86.00	7.00
2017	3	99.00	103.00	92.00	6.08	4	97.88	108.00	92.00	7.62	1	68.50	68.50	68.50	N/A

Drainage Basin 8

2011	3	63.80	67.20	58.80	4.42	2	65.25	66.00	64.50	1.06	1	59.50	59.50	59.50	N/A
2012	3	64.33	70.50	61.00	5.35	2	62.00	64.50	59.50	3.54	2	64.00	64.50	63.50	0.71
2013	2	66.75	68.00	65.50	1.77	4	60.50	63.00	57.00	2.65	4	64.75	65.50	64.00	0.65
2014	3	59.83	61.50	58.00	1.76	6	61.96	68.00	57.00	3.68	1	58.50	58.50	58.50	N/A
2015	3	64.42	69.00	61.50	4.02	6	64.33	66.75	61.00	2.51	3	61.75	69.25	55.50	6.96
2016	5	61.00	62.75	59.50	1.57	5	62.10	66.50	57.50	3.49	3	62.00	65.00	57.00	4.36
2017	2	58.00	60.50	55.50	3.54	4	59.81	62.50	56.25	2.79	1	47.00	47.00	47.00	N/A

APPENDIX F: Summary statistics for changes in depth to groundwater by water year for groundwater wells: Blackman, Curlew, Juncos #1, Juncos #2, Nags Head Control, Nags Head Fire Station, Old Cove #1, Old Cove #2.

Water Year	Changes in Depth to Groundwater				
	Count	Mean	Max	Min	StdDev
Blackman					
2011	6	35.80	48	24	8.83
2012	8	21.94	33	8	7.79
2013	5	24.80	27	24	1.25
2014					
2015					
2016					
2017					
Curlew					
2011	6	42.57	52	32.4	9.38
2012	8	22.94	37	13	8.07
2013	10	31.15	47	21	6.49
2014	11	27.91	38	17	6.58
2015	12	33.13	42.5	21	6.34
2016	13	26.96	36	22	4.55
2017	8	30.75	38	16	6.54
Juncos #1					
2011	6	15.50	21	10.8	3.25
2012	7	9.29	13	4	2.93
2013	10	13.90	21	7	4.68
2014	11	13.77	18	9	3.16
2015	12	19.21	27	9	5.40
2016	13	10.08	17.5	4.5	4.09
2017	8	10.13	16	5	3.35

Juncos #2

2011	6	20.33	34	13.2	7.21
2012	7	15.29	22	8	5.22
2013	9	21.44	32	9	7.80
2014	11	21.23	31	11	5.50
2015	12	26.92	37	12.5	6.48
2016	13	16.81	29	7	5.86
2017	8	18.81	23	10	4.17

Nags Head Control

2011	7	105.03	150	69	37.61
2012	8	60.06	67	56	3.93
2013	10	65.00	71	59	4.57
2014	11	61.45	67	57	3.33
2015	12	65.33	72	56	4.66
2016	13	61.93	69	56	3.61
2017	8	59.94	65	48	5.37

Nags Head Fire Station

2011	7	96.00	115.2	84	11.13
2012	7	86.86	105	54	20.14
2013	10	95.10	108	75	10.54
2014	11	90.55	104	80	7.36
2015	12	95.38	105	84	7.14
2016	13	86.73	100	73.5	9.72
2017	8	94.63	108	68.5	12.13

Old Cove #1

2011	6	75.83	82.8	70	5.07
2012	7	78.43	88	72	5.38
2013	10	77.30	83	71	3.53
2014	11	75.32	84	72	3.95
2015	12	78.08	82.5	70	3.61
2016	13	74.85	78	71	2.45
2017	7	70.64	76	60	5.22

Old Cove #2

2011	6	51.30	56.4	46.8	3.24
2012	7	48.71	58	41	5.31
2013	10	49.60	53	42	3.34
2014	11	48.45	58	41	5.05
2015	12	49.33	57	41	4.66
2016	13	48.46	55	43	3.97
2017	7	44.29	51	34	5.65

APPENDIX G: Field Data Tables containing field measurements for conductivity, salinity, temperature, and dissolved oxygen for all sampling events. These data were not used for analysis as correlations between observed data and nutrient and bacteria analysis were not found to be significant. Blank spaces in tables signify sample events where water levels at sample locations were too low for collection.

Conductivity (µS)

Location and Date	**10/5/18**	**10/10/18**	**10/24/18**	**10/26/18**	**10/27/18**
GW1	249.4	207.9	213.8	220.4	227.6
GW2	237.5	273.4	124.5	225.4	221.7
OF	44160	44220	39080	43630	38480
SW1	233	230.6			46.5
SW2	513	500	548	250	268
SW3	505	504		360	280

Salinity (ppt)

Location and Date	**10/5/18**	**10/10/18**	**10/24/18**	**10/26/18**	**10/27/18**
GW1	0.1	0.1	0.1	0	0.1
GW2	0.1	0.1	0.1	0.1	0.1
OF	29	29.2	30.3	28.2	29.6
SW1	0.1	0.1			
SW2	0.2	0.2	0.3	0.1	0.1
SW3	0.2	0.2		0.2	0.2

Temperature (^{0}C)

Location and Date	**10/5/18**	**10/10/18**	**10/24/18**	**10/26/18**	**10/27/18**
GW1	18	18.3	16.5	16.9	16.6
GW2	23.2	24	20.7	19.6	20.6
OF	24.2	24.4	16.6	15.9	16.8
SW1	22.3	26.1			16.7
SW2	24.1	23.7	18.5	14.6	16.9
SW3	24.5	24.3		12.9	16.3

Dissolved Oxygen (mg/L)

Sample	**10/5/18**	**10/10/18**	**10/24/18**	**10/26/18**	**10/27/18**
GW1	5.15	3.28	2.21	2.3	2.79
GW2	5	2.8	3.64	3.11	3.78
OF	6.64	5.49	5.84	6.95	6.98
SW1	0.39	3.04			6.52
SW2	2.6	3.17	10.6	4.63	2.64
SW3	4.43	5.76		9.65	2.49