Climate Change and Onsite Wastewater Treatment Systems in the Coastal Carolinas

A view of the Town of Nags Head, N.C. in the Outer Banks. Photo by Charlie Cowins/flickr/CC BY 2.0

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Funding Source

NOAA Climate Program Office NOAA-OAR-CPO-2019-2005530

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Foreword

The Carolina coast faces increasing environmental impacts from a changing climate, leading to critical infrastructure challenges. One such problem that deserves attention is onsite wastewater treatment.

While urban areas often rely on large centralized sewage treatment plants to dispose of wastewater, many coastal communities depend on onsite systems. Because much of the Carolina coast is less densely populated, the cost of centralized treatment can be challenging. Almost half of residents in North and South Carolina rely on onsite wastewater treatment systems (OWTS), either individual onsite septic systems or small community cluster systems.

As climate changes, OWTS are increasingly vulnerable to malfunction or even failure if exposed to storm surges, sea level and groundwater level rise, and heavy rainfall – events that are predicted to increase in frequency and severity with climate change.

Understanding how OWTS are functioning in a changing climate along the Carolina coast involves ongoing research by a team from East Carolina University. Concurrently, research partners from NC Sea Grant, NC State University and University of Georgia are investigating industry and regulatory approaches, as well as economic and legal constraints and opportunities.

In this report, you'll learn about the coastal areas in the Carolinas where these issues are being studied, including predicted climate impacts and data on monitoring sites observed for wastewater contaminants. Next, perspectives from onsite wastewater treatment experts are provided, and finally legal and economic adaptation options. Two case studies – adaptation in Nags Head, North Carolina and Folly Beach, South Carolina – are presented to illustrate potential adaptation pathways for coastal communities.

Recommendations are provided to illuminate pathways for coastal municipalities, government entities, and individual households to develop adaptation strategies for OWTS in the face of rising sea levels and a changing climate.

Explore the report to gain a deeper understanding of how climate change impacts coastal communities and what can be done to protect vital infrastructure and the people and environment who depend on it.

Recommendations

1. Maintain all OWTS for proper functionality to ensure effective treatment of bacteria, nitrogen and phosphorus. Properly sited conventional, advanced and cluster systems are critical infrastructure for human and environmental health. **See table 2.2 and sections 4.1 - 4.5**.
    - Incentivize routine inspection and pump outs of conventional OWTS by municipalities/counties and identify those performing poorly for upgrades. Pollution reduction via routine maintenance is a low cost solution. **See sections 5.2, 5.3, 6.1, 6.4, 7.**
    - Convert conventional OWTS to advanced systems or package treatment plants in areas with shallow groundwater levels and insufficient vertical separation distance or elevate those systems. **See sections 2.2, 3.4, 5.3, 6.4, 7.1, 7.3, 7.4.**
    - Connect households with underperforming systems to municipal wastewater treatment facilities if population density is sufficient to make cost viable and environmental permits can be secured. **See sections 6.3, 6.4, 7.1, 7.3, 7.4, 7.7.**
2. Incorporate weather and climate risk in OWTS site approval and system selection; consider risk of acute failures due to extreme precipitation, sea level rise, and groundwater level changes for oceanfront, sound side, and inland coastal communities. **See sections 1, 5.1, 5.2.**
3. Build adaptive capacity in communities and municipalities at high risk for climate impacts.[1]
    - Implement comprehensive outreach and education programs to raise awareness with the public and OWTS managers (operators, installers, regulators) about the risks of disruptive weather events to OWTS and the need to implement and strengthen climate adaptation measures for OWTS in coastal communities. **See section 5.4.**
    - Key stakeholders include municipalities, OWTS managers, health regulators, state legislators, fisheries/environmental stakeholders, NC Department of Environmental Quality, and system owners/operators.
4. Create digital long-term inventories (state or national) of OWTS, focusing on coastal communities, to enable system monitoring and evaluation. **See sections 5.2, 5.3, 6.4.2, 6.5.2.**
    - Inventories should include system location, age, type (e.g. conventional, advanced), depth to water table, land surface elevation, condition, repair permits, and history of malfunction to monitor OWTS status and identify key areas or hotspots for improvement.
    - Standardizing the collection of this information from operation and repair permits during on-site evaluations and digitization would build capacity for such an inventory.
5. Educate local governments on the extent of their authority to regulate the use of OWTS, including siting, required technologies and inspections, and post-installation management. **See sections 6.1 - 6.5.**

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[1] "Adaptive capacity is the potential or ability of a system, region, or community to adapt to the effects or impacts of climate change. Enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes." Definition accessed from IPCC Archives: Reports - Assessment Reports, Working Group II: Impacts, Adaptation and Vulnerability, 2022. *IPCC Publications and Data, Reports*, https://archive.ipcc.ch/ipccreports/tar/wg2/index.php?idp=643.

6. Upgrade cesspools and straight discharge systems first. This approach reduces the most pollution at the lowest cost. **See sections 7.3, 7.4.**

7. Set aside municipal land for cluster system siting to encourage the adoption of these high-performing systems. This would address the problem of land costs being a key prohibitive factor in the affordability of advanced treatment via cluster systems. **See sections 6.1, 6.3, 6.4, 7.2, 7.3.**

8. Assess feasibility of reusing wastewater to reduce use of deeper groundwater and prevent subsidence (sinking of the ground surface in response to geological or man-induced causes). Reuse would reduce wastewater inputs to surficial aquifers which can contribute to rising groundwater. **See sections 3.2, 3.3.**

1. Predicted climate impacts for the coastal Carolinas

By Jared Bowden, Ph.D., Department of Applied Ecology, North Carolina State University

As the climate warms, sea levels rise, precipitation characteristics change, and the atmospheric evaporative demand increases. Collectively, changes in these processes will impact future groundwater levels, with significant impacts to the coastal Carolinas and onsite wastewater infrastructure. Increased sea-level rise and mean precipitation increases that exceed evaporation demand are already contributing to higher groundwater levels, which impair OWTS along the coast by reducing availability of unsaturated soil for treatment. Additionally, changes in extreme weather events that create flooding compromise treatment and may persist days to weeks after the event as groundwater levels slowly decline. Here we discuss observed and projected changes in the climate system that impact onsite wastewater treatment as it pertains to the coastal Carolinas.

1.1 Sea level rise in the coastal Carolinas

Global sea level has risen by approximately 7.9 in. [0.2m] between 1901 and 2018 with the average rate of sea level rise accelerating in the most recent decades. For instance, the rate of change from 1971-2006 is estimated to be 0.07 in./year [1.9 mm/year] and 0.15 in./year [3.7 mm/year] from 2006 to 2018 – an almost doubled rate of change in the most recent decade[2]. Observed sea level rise along the coastal Carolinas is location dependent with the rate of change being largest along northeastern North Carolina[3] (e.g., +0.19 in./year [+4.78 mm/year] at Duck, N.C. on the state's northern coast; 0.10 in./year [+2.61 mm/year] at Wilmington, N.C. on the state's southern coast; 0.13 in./year [+3.39 mm/year] at Charleston, S.C.[4]). The impacts from sea level rise on coastal communities are escalated by astronomical high tides, commonly referred to as "sunny day" or "nuisance floods." The number of "nuisance flooding" events has increased by 5 to 10-fold since the 1960s and is accelerating for Atlantic and Gulf Coast cities[5]. When considering subsurface infrastructure like conventional onsite wastewater infrastructure, an additional related hazard is the associated relationship between groundwater level rise and sea level rise[6], especially for near-shore areas[7].

Future projections of sea level rise rely on climate model simulations. Climate models are designed to simulate changes in the earth's climate to changes in atmospheric concentrations of greenhouse gas emissions, aerosols, chemically active gases, and land-use changes. Here we discuss recent sea level rise

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[2] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

[3] Kunkel, K.E., D.R. Easterling, A. Ballinger, S. Bililign, S.M. Champion, D.R. Corbett, K.D. Dello, J. Dissen, G.M. Lackmann, R.A. Luettich, Jr., L.B. Perry, W.A. Robinson, L.E. Stevens, B.C. Stewart, and A.J. Terando, 2020: North Carolina Climate Science Report. North Carolina Institute for Climate Studies, 233 pp. https://ncics.org/nccsr

[4] NOAA Sea Level Rise Trends; https://tidesandcurrents.noaa.gov/sltrends/; accessed on 4/1/2022

[5] Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA (2017), pp. 493-539.

[6] Manda, A. K., Sisco, M. S., Mallinson, D. J. and Griffin, M. T. 2015: Relative role and extent of marine and groundwater inundation on a dune-dominated barrier island under sea-level rise scenarios. Hydrol. Process., 29: 1894– 1904. doi: 10.1002/hyp.10303.

[7] May, C., 2020: Rising groundwater and sea-level rise. Nature Climate Change, 10(10), 889-890. doi:http://dx.doi.org/10.1038/s41558-020-0886-x

projections[8] with targeted focus on northeastern North Carolina; Nags Head, N.C.; and Folly Beach, S.C. There are four sea level rise scenarios for global mean sea level rise by 2100: Intermediate Low (0.3 m [0.98 ft]), Intermediate (0.5 m [1.64 ft]), Intermediate High (1.0 m [3.28 ft]), and High (2.0 m [6.56 ft]). These global mean sea level rise projections are sensitive to the mean amount of warming by 2100 – the greenhouse gas emission scenarios commonly referred to as the Shared Socioeconomic Pathways (SSPs)[9], Table 1.1.

Table 1.1 Sea level rise scenarios with global sea level rise projections for 2100 with the approximate greenhouse gas emission scenario and mean global warming by 2100.

Sea level rise scenario	Global sea level rise	Mean global temp. Increase	Greenhouse gas emission scenario
Intermediate (Int.) Low	0.98 ft [0.3 m]	3.6°F [2°C]	SSP1-2.6
Intermediate (Int.)	1.64ft [0.5 m]	5.4°F [3°C]	SSP2-4.5
Intermediate (Int.) High	3.28 ft [1.0 m]	7.2°F [4°C]	SSP3-7.0
High	6.56 ft [2.0 m]	9.0°F [5°C]	SSP5-8.5

Figure 1.1 is an illustration of inundation from future sea level rise for northeastern North Carolina. This potential future flooding from sea level rise is as it would appear during highest high tides excluding wind driven tides. The maps were created using the NOAA Sea Level Rise Viewer – a screening-level tool designed to help visualize potential impacts from sea level rise[10]. Included in the plots are estimated dates with sea level rise estimates for different scenarios from 1 to 3 ft [0.3m to 0.9m]. By 2040, all estimates indicate 1ft of sea level rise, which will impact mostly near coastal locations within northeastern North Carolina. Sea level rise causes a drastic increase of inundated areas, especially within Dare, Hyde, and Tyrell counties. Sea level rise projections of 2ft [0.6m] occur for all scenarios with earliest emergence around mid-century for the High scenario and end-century for Int. Low scenario. Three feet of sea level rise has a notable impact on Dare and Tyrell counties and is projected for all but the Int. Low scenario.

[8] Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D.White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf

[9] Riahi, K. et al. 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change 42, 153–168.

[10] NOAA Sea Level Rise Viewer; https://coast.noaa.gov/slr/#/layer/slr.

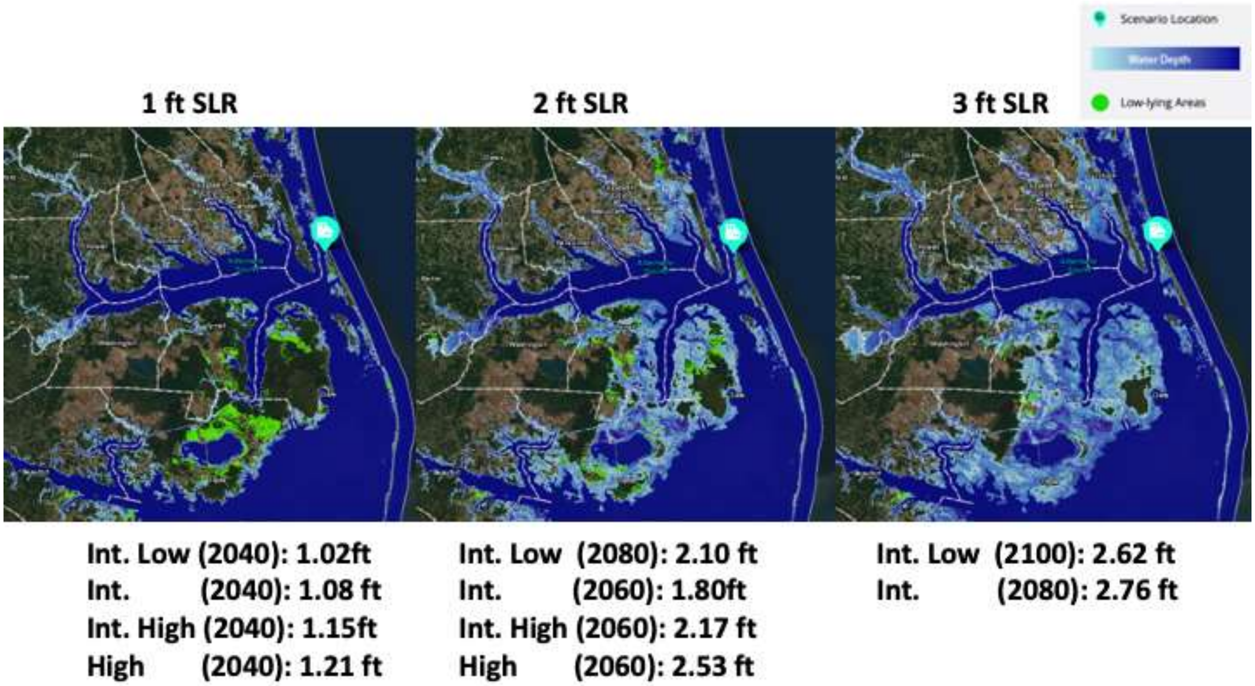


Figure 1.1. Sea level rise inundation for northeastern NC. Included are the sea level rise scenarios, dates, and sea level rise values that are approximated to sea level inundation from 1ft [0.3m] to 3ft [0.9m]. Blue shading represents inundation water depth (darker blue=deeper water levels). Green shading represents low-lying areas.

Figure 1.2 provides a more focused view in and around Nags Head, N.C. Vulnerable places with 1ft of sea level rise include several sound side locations from Kitty Hawk to Kill Devil Hills and Wanchese and occurs for all scenarios before mid-century. At 2ft [0.6m] of sea level rise, much of Roanoke Island and the sound side of the barrier island including areas around Nags Head become inundated as early as mid-century for the High scenario and around 2080 for the Int. Low Scenario. A particular concern for wastewater treatment is inundation along the sound side. These locations are likely at more immediate threat of treatment failure as a direct result of sea level rise.

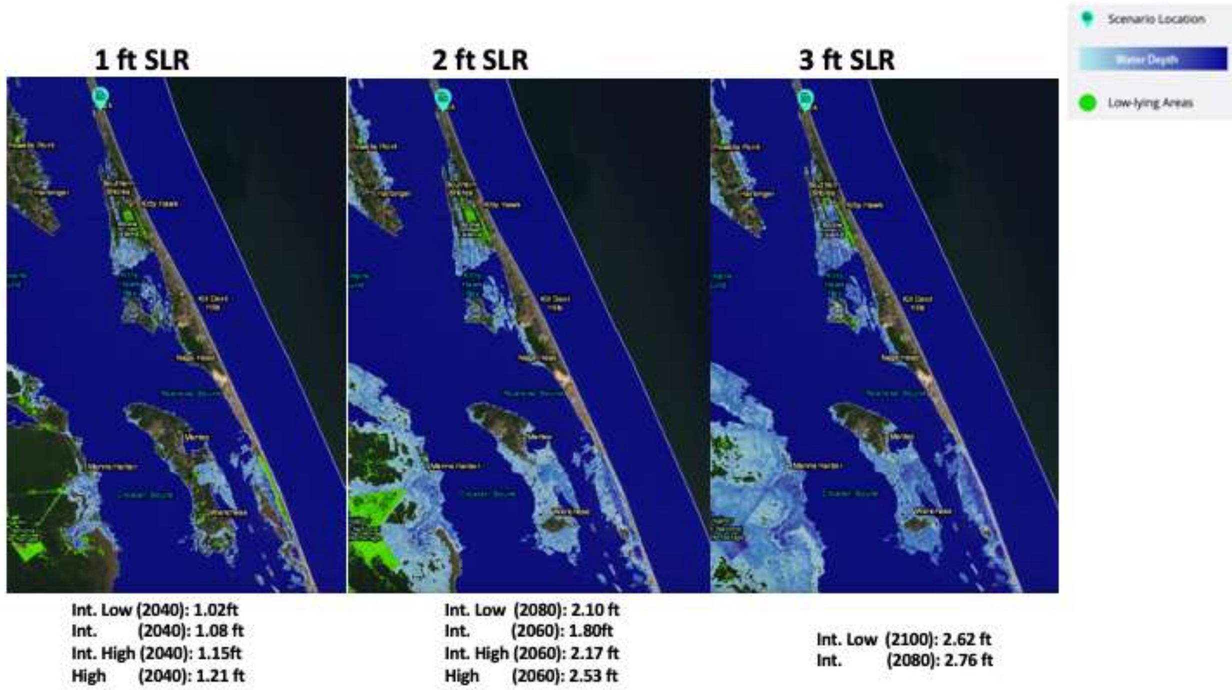


Figure 1.2. Same as Figure 1.1 but for Nags Head, N.C.

Figure 1.3 provides a more focused view in and around Folly Beach, S.C. Particularly vulnerable areas for inundation, even with 1ft of sea level rise, are located for the southern half of Folly Beach, especially the lower elevations on the sound side. With 2ft [0.6m] of sea level rise, inundation begins to have a significant impact on the northern tier of Folly Beach and for lower elevations on the sound side. Similar to Nags Head, one concern for onsite wastewater treatment is the risk of failure as a result of inundation on the sound side.

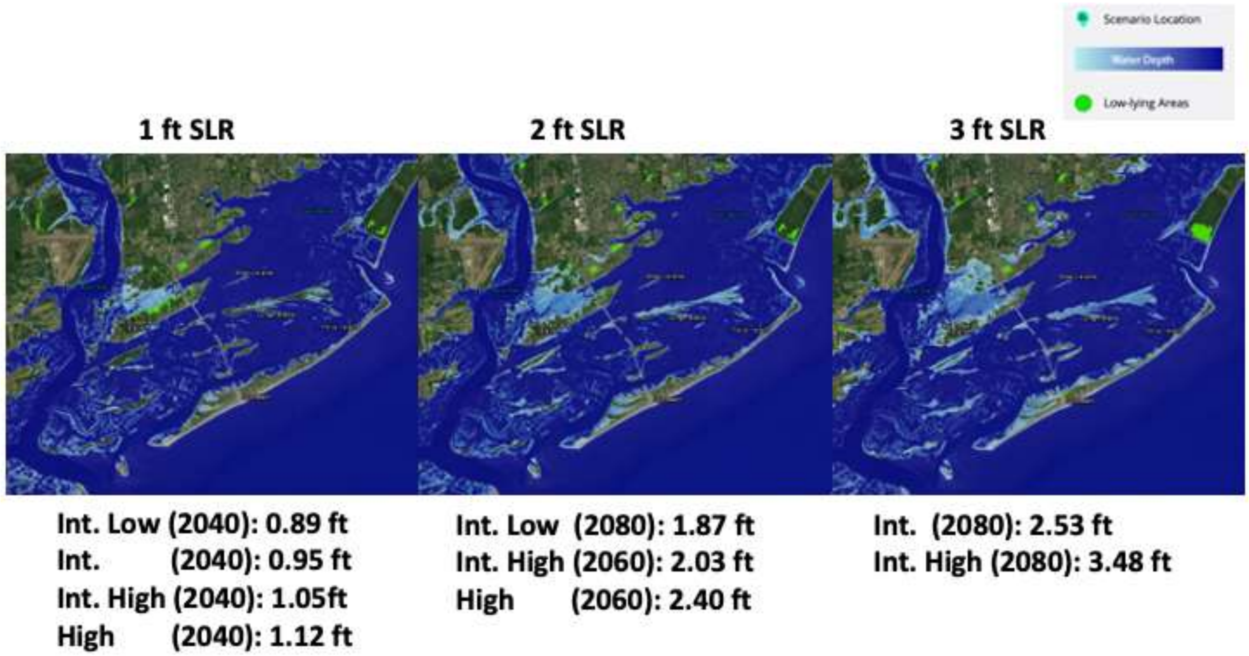


Figure 1.3. Same as Figure 1.1 but for Folly Beach, SC.

1.2 Observed changes for temperature and precipitation within the coastal Carolinas

For North Carolina, the annual average temperature has increased by 1°F since the beginning of the 20th century and has been consistently above average since the 1990s relative to the long-term average (1901-1960)[11]. In particular, summer averages in the recent decades have been the warmest on record. There is a notable increase in the number of very warm nights (minimum temperature >=75°F) in recent decades, but no discernable increase in the frequency of very hot days (maximum temperature >=95°F). As for precipitation, on average for the state there is no long-term trend in the annual total precipitation; however, there is an indication that a larger portion of the annual total rainfall is occurring in heavy events. For instance, the number of 3-inch extreme precipitation events was highest for the most recent 5-year period from 2015-2020 since 1900. This time period included the torrential rainfall events of Hurricanes Matthew (2016 with upwards of 18.95 inches) and Florence (2018 with upwards of 36 inches of rainfall)[12]. For North Carolina, the climate metric of most concern for onsite wastewater treatment is the observed change in extreme precipitation. Changes in extreme rainfall events, such as rainfall associated with major hurricanes, have been shown to increase groundwater levels which can inundate the drainfield trenches of OWTS, leading to direct discharge of wastewater to groundwater. For instance,

[11] Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, W. Sweet, A. Wootten, H. Aldridge, R. Boyles, and S. Rayne, 2022: North Carolina State Climate Summary 2022. NOAA Technical Report NESDIS 150-NC. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[12] Kunkel, K.E., D.R. Easterling, A. Ballinger, S. Bililign, S.M. Champion, D.R. Corbett, K.D. Dello, J. Dissen, G.M. Lackmann, R.A. Luettich, Jr., L.B. Perry, W.A. Robinson, L.E. Stevens, B.C. Stewart, and A.J. Terando, 2020: North Carolina Climate Science Report. North Carolina Institute for Climate Studies, 233 pp. https://ncics.org/nccsr

groundwater levels with Hurricane Florence rose over 4.92 ft [1.5m] within 9 hours, but took more than 3.6 weeks to return to pre-storm levels[13].

For South Carolina, the annual average temperature has increased by 1°F since the beginning of the 20th century[14]. The number of extremely hot days (maximum temperature >=100°F) has been near average since 1980, but the number of very warm nights (minimum temperature > 75°F) have been above average since 1980, similar to North Carolina. Similarly, there is no overall trend in annual precipitation since 1900; however, the most recent 5-year period (2015-2020) was well above average with an increase in the number of 3-inch extreme precipitation events. In October 2015, torrential rainfall was observed in coastal South Carolina including 21.5 inches at Folly Beach from Oct. 2-6 – the result of a complex weather pattern that involved Hurricane Joaquin[15]. Similar to North Carolina, observed changes in heavy rainfall (frequency and magnitude) in recent years is a major concern for onsite wastewater treatment as groundwater can quickly rise and inundate these systems.

1.3 Projected changes for temperature, precipitation, and potential evapotranspiration within the coastal Carolinas

Climate change projections for the coastal Carolinas are shown for mean temperature, precipitation, potential evapotranspiration, and precipitation minus mean potential evapotranspiration (**Figures 1.4-1.7**) for winter (December, January, February) and summer (June, July, August). Potential evaporation is simply the amount of evapotranspiration that would take place for a surface with unlimited water (e.g., an open pan of water). These figures help us understand plausible changes in the climate that would impact mean groundwater levels and OSWT. For instance, positive differences between projected changes in seasonal precipitation (groundwater supply) and seasonal potential evapotranspiration (groundwater demand) indicate that mean precipitation exceeds evaporation demand with a plausible increase in mean groundwater levels in the future. Here we provide climate change projections for mid-century (2040-2069) and end-century (2070-2099) for two greenhouse gas emission scenarios (Representative Concentration Pathways - RCP4.5 and RCP8.5[16]) relative to a baseline historical period (1971-2000) are shown. RCP4.5 is an emission scenario in which emissions increase until around mid-century and then slowly decline – a climate mitigation scenario. RCP8.5 is a scenario where emissions continue to increase throughout the course of this century – a business as usual scenario. All projections use statistically downscaled global climate model data from the Coupled Model Intercomparison Project 5 utilizing a modification of the Multivariate Adaptive Constructed Analogs (MACA) method with the METDATA observational dataset as training data[17].

By mid-century, increases in mean annual temperature (**Figure 1.4**) for both emission scenarios indicate increases between 3-5°F with larger increases found during the summer season and the higher emission

[13] Charles Humphrey Jr., Danielle Dillane, Guy Iverson, Michael O'Driscoll; Water table dynamics beneath onsite wastewater systems in eastern North Carolina in response to Hurricane Florence. *Journal of Water and Climate Change* 1 August 2021; 12 (5): 2136–2146. doi: https://doi.org/10.2166/wcc.2021.303

[14] Runkle, J., K.E. Kunkel, L.E. Stevens, R. Frankson, B.C. Stewart, W. Sweet, and S. Rayne, 2022: South Carolina State Climate Summary 2022. NOAA Technical Report NESDIS 150-SC. NOAA/NESDIS, Silver Spring, MD, 5 pp

[15] Marciano, C.G., and Lackmann, G.M., 2018: The South Carolina Flood of October 2015: Moisture Transport Analysis and the Role of Hurricane Joaquin, Journal of Hydrometeorology, 18(11), 2973-2990.

[16] van Vuuren, D.P., Edmonds, J., Kainuma, M. *et al.*, 2011. The representative concentration pathways: an overview. *Climatic Change* **109,** 5. https://doi.org/10.1007/s10584-011-0148-z

[17] Abatzoglou J.T. and Brown T.J. "A comparison of statistical downscaling methods suited for wildfire applications " International Journal of Climatology (2012),doi: 10.1002/joc.2312.

scenario (RCP8.5). Climate mitigation has a significant impact on mean temperature increases by end-century with a near doubling of the average regional mean temperature from ~4°F for RCP4.5 to 8°F for RCP8.5. This is an important aspect when considering future groundwater because potential evapotranspiration increases as mean temperature increases. Overall, increased evapotranspiration favors increased groundwater depth during the summer months, which favors availability of unsaturated soil available needed for OWTS.

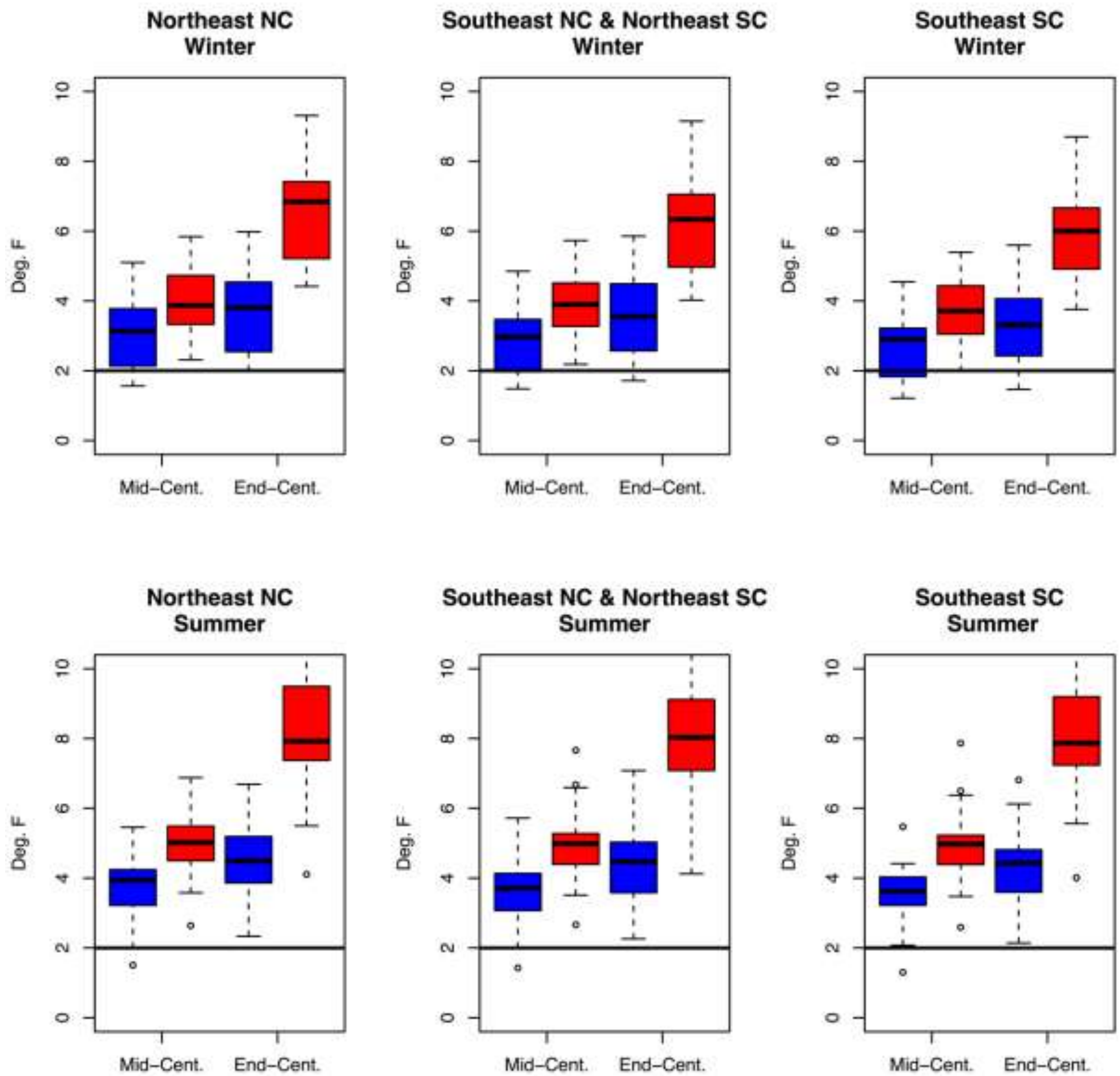


Figure 1.4. Projected change temperature (°F) from 20 downscaled global climate models for RCP4.5 (blue) and RCP8.5 (red) at mid-century and end-century. Top (bottom) 3 panels are the average change for the winter (summer) season averaged over three different coastal regions (Northeast NC, Southeast NC/Northeast SC, and Southeast SC).

To better diagnose the plausible impact of climate change on groundwater, Figures 1.5-1.7 illustrate important components that impact groundwater including precipitation (supply) and potential evapotranspiration (demand) and relative differences (precipitation minus potential evapotranspiration). During the winter months, there is a general increase in mean for precipitation to supply groundwater (Figure 1.5); however, this is countered by increases in potential evapotranspiration (Figure 1.6), which are on the same order with an exception for the high emission scenario by end-century where potential evapotranspiration exceeds precipitation. Overall, for the winter season there remains the plausibility that changes in the mean average state for groundwater rises as a direct result of mean precipitation exceeding evaporation creating additional stress for OWTS. Groundwater rise as a result of mean precipitation changes becomes increasingly less likely for the summer season where slight increases in the mean precipitation are exceeded by large increases in potential evapotranspiration, especially for the RCP8.5 scenario at both mid and end-century. In the absence of sea level rise and storm-driven flooding, increasing aridity on average during the summer months will likely lower the groundwater levels, thereby increasing separation distance and providing additional capacity to treat wastewater. Increased separation distances will likely improve removal of pathogens and provide additional cation-exchange sites for phosphorus removal since these processes mostly occur in the vadose zone. However, nitrogen removal may be inhibited since removal requires saturated conditions and sufficient organic carbon to facilitate denitrification. Carbon may be limited in deeper soil horizons, thus limiting nitrogen removal. Furthermore, increasing ariditiy may result in reduced groundwater flow in the surficial aquifer, which hinders dilution and could increase nutrient input to shallow groundwater systems. Reducing treatment capacity of OWTSs may result in discharge of inadequately treated wastewater to shallow groundwater (and eventual discharge to surface water) or directly to surface bodies during malfunction. This effluent may contain elevated nutrients, which can destablize aquatic ecosystems via eutrophication and algal blooms. Effluent may also contain elevated bacteria, which can result in the closure of recreational waters and shellfishing fisheries. Additionally, this has implications for wastewater treatment plants (WTPs). Increased aridity favors low baseflow volume in rivers, which may impact the spatial extent of mixing zones downstream of WTP effluent discharge points. These mixing zones are areas adjacent to effluent discharge points where mixing of WTP effluent and river water dilutes concentrations of residual contaminants in the WTP effleunt. Therefore, future climate conditions that reduce a river's dilution capacity may increase the downstream extent of these mixing zones, potentially endangering aquatic habitat for sensitive species.

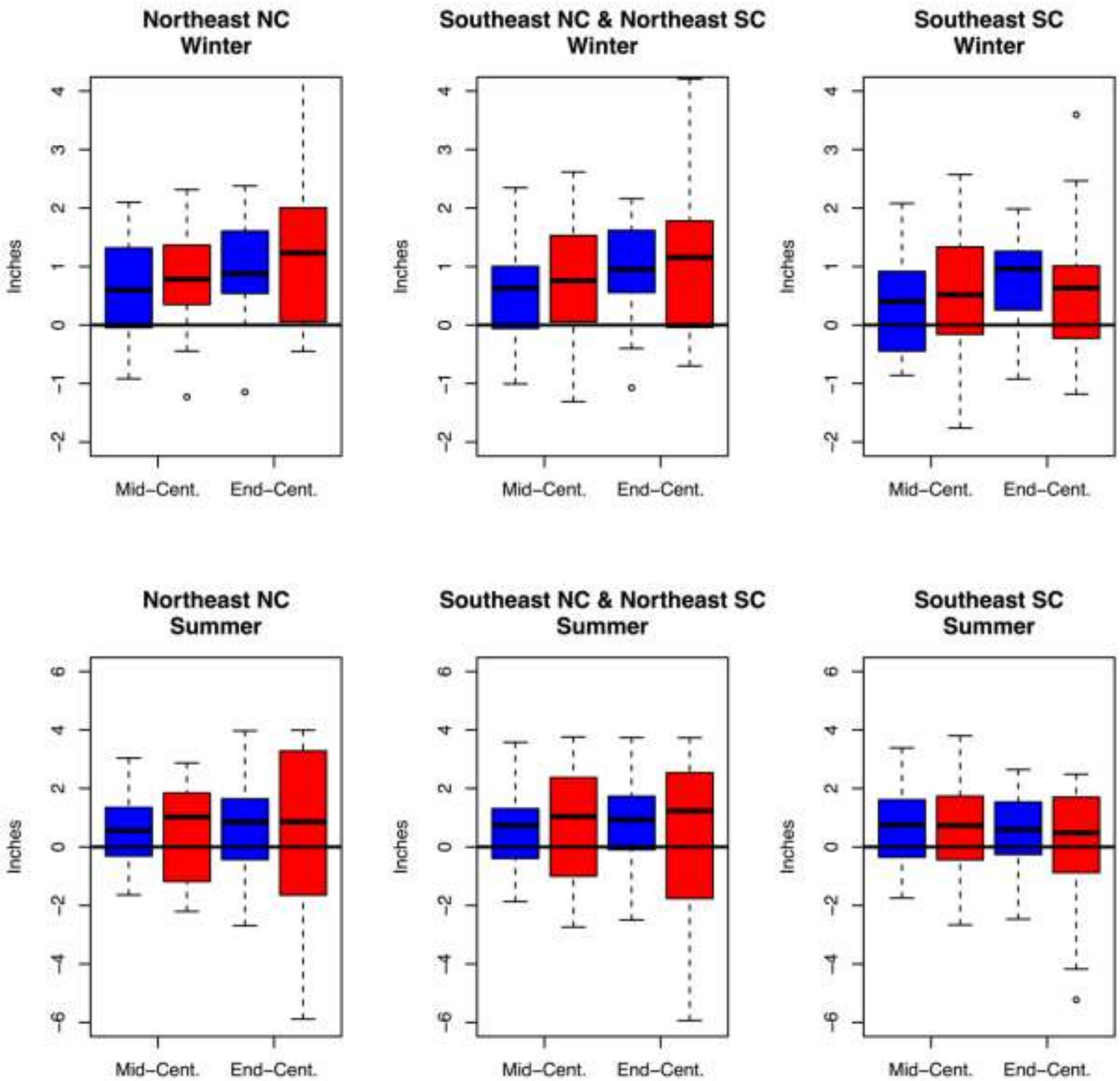


Figure 1.5. Same as Figure 1.4 but for precipitation (inches).

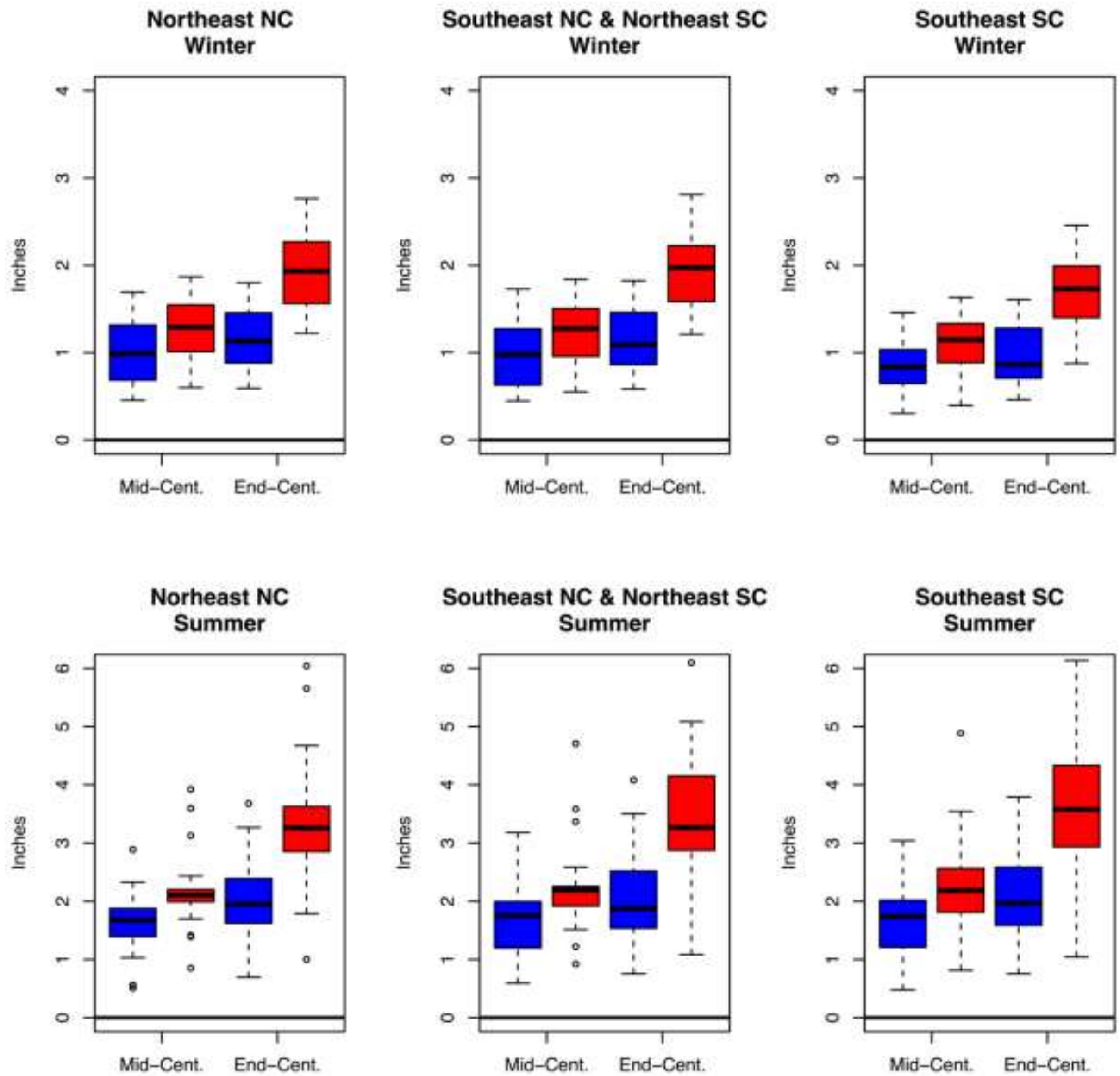


Figure 1.6. Same as Figure 1.4 but for potential evapotranspiration (inches).

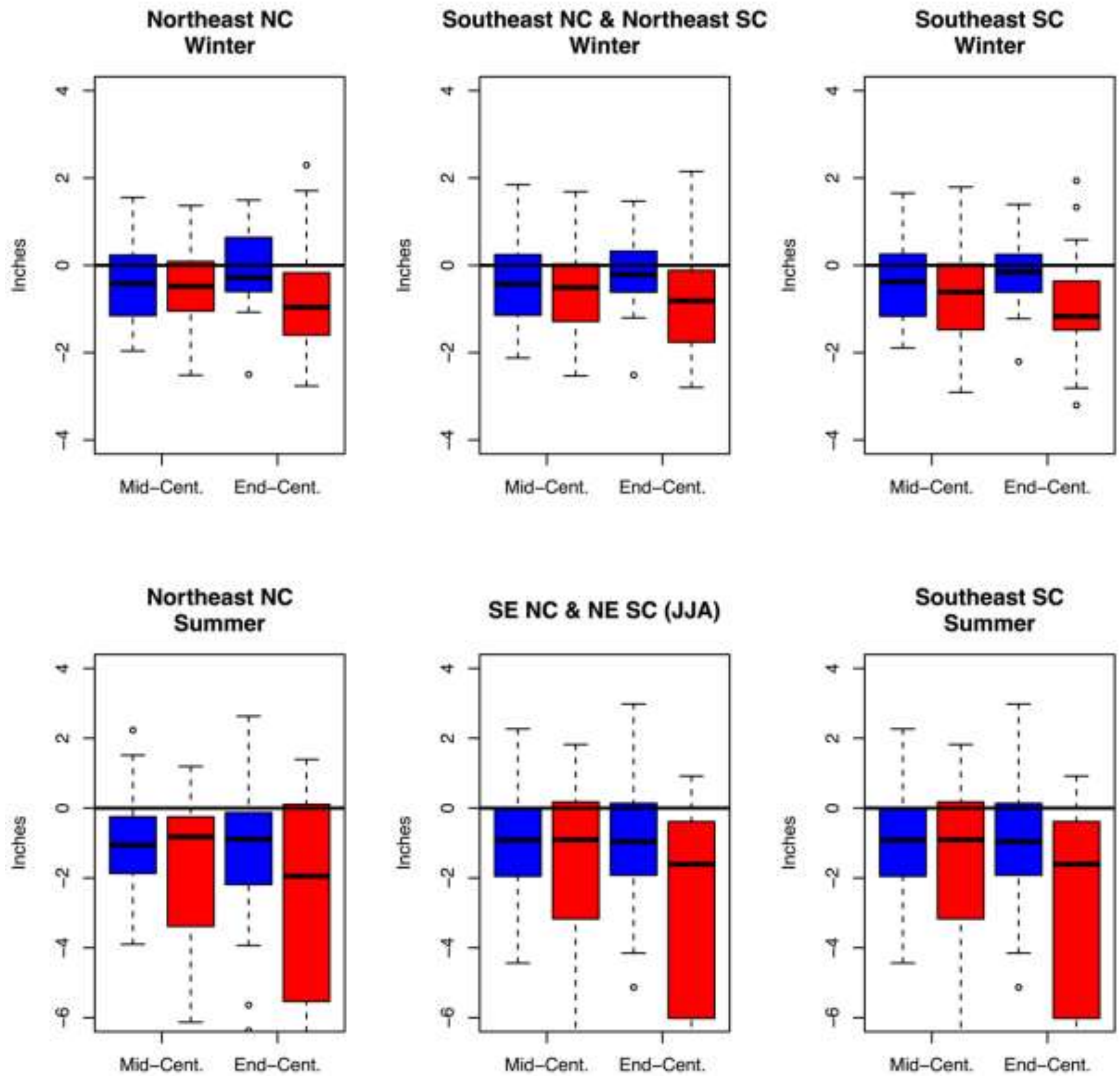


Figure 1.7. Same as Figure 1.4 but for precipitation minus potential evapotranspiration (inches).

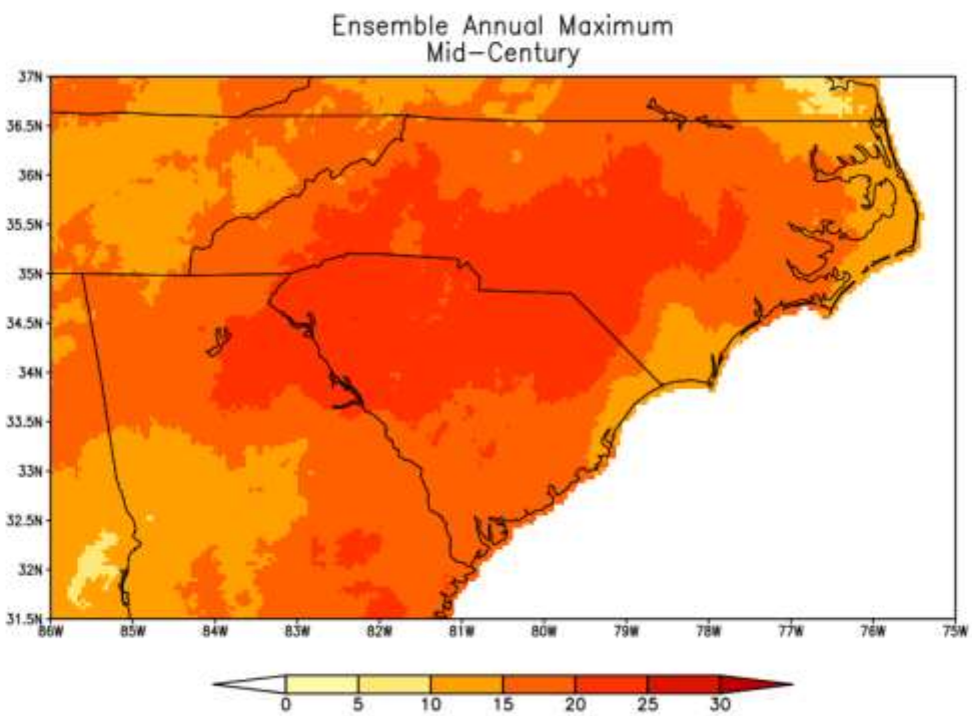
Rainfall characteristics associated with extreme weather events are anticipated to change as the climate warms.[18] [19] For instance, tropical cyclone precipitation rates are projected to increase in the future as a result of increasing atmospheric moisture capacity as temperature increases.[20] A study exploring the potential changes in extreme rainfall across Eastern North Carolina for 2025-2100 from tropical cyclones

[18] Blenkinsop, S., Muniz Alves, L., and Smith, A.J.P., 2021: ScienceBrief Review: Climate change increases extreme rainfall and the chance of floods. In: *Critical Issues in Climate Change Science*, edited by: C. Le Quéré, P. Liss, P. Forster. https://doi.org/10.5281/zenodo.4779119.

[19] Michaelis, A.C, and Lackmann, G.M. 2021: Storm-Scale Dynamical Changes of Extratropical Transition Events in a Present-Day and Future High-Resolution Global Simulations, Journal of Climate (published online).

[20] Knutson, T., et al. 2020. Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming, Bulletin of the American Meteorological Society, 101 (3), E303-E322.

found that maximum rainfall intensities could increase by 168% in some areas, and widespread regional rainfall increases could increase up to 44%.[21] To better understand rainfall intensity changes for the coastal Carolinas, the daily rainfall maximum is calculated for each year and then averaged for a historical (1976-2005) and future periods (2040-2069; 2070-2099) for each downscaled GCM data for the high greenhouse gas emission scenario. Figure 1.8 illustrates the relative difference in daily rainfall maximum (a.k.a. annual maximum series) averaged for mid and end century. Rainfall intensity is projected to increase for the largest daily rainfall events upwards of 15% by mid-century and 30% by end-century for the high greenhouse gas emission scenario. The risk to onsite wastewater treatment will increase as rainfall intensity increases, likely creating acute problems for these systems. For instance, in the summer the increasing aridity may create more favorable conditions for lower groundwater levels, but a more intense rainfall event (e.g., intense rainfall from localized thunderstorm) can quickly cause the groundwater levels to rise and impair treatment. Increases in groundwater variability may be anticipated as the intensity of extreme weather events increase in a warmer climate which would make wastewater treatment more variable in the future.



[21] Jalowska, A. M., T. L. Spero, and J. H. Bowden, 2021: Projecting changes in extreme rainfall from three tropical cyclones using the design-rainfall approach. npj Climate and Atmospheric Science, 4 (23), https://doi-org.prox.lib.ncsu.edu/10.1038/s41612-021-00176-9.

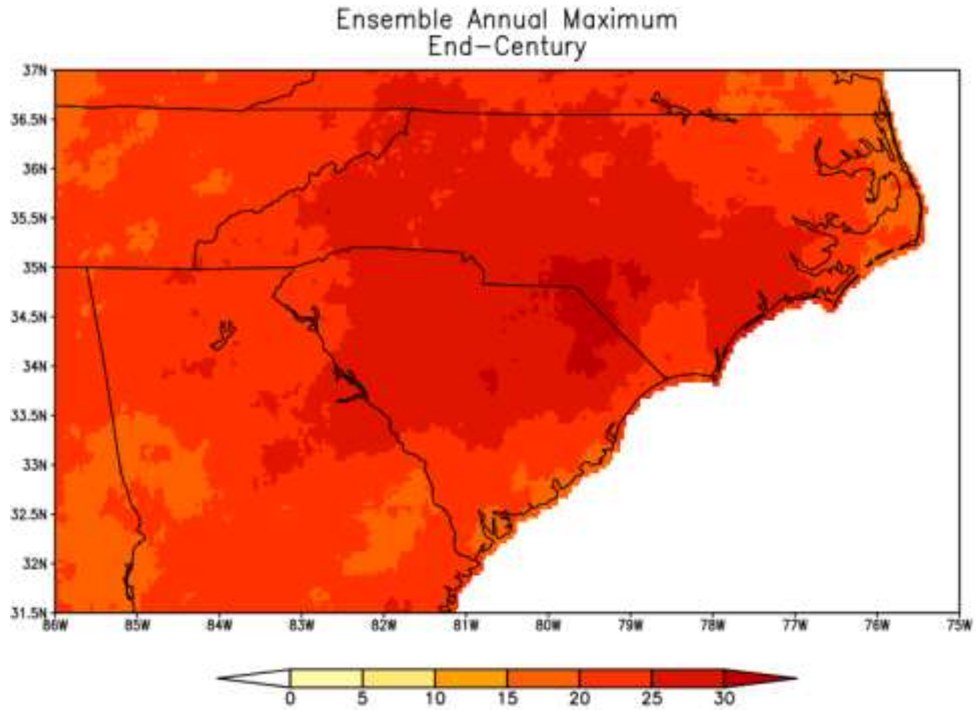


Figure 1.8. Relative change (%) in mean of the daily annual maximum precipitation for mid-century (2040-2069) and end-century (2070-2099) relative to the baseline historical period (1976-2005).

2. Onsite wastewater treatment in a changing climate

By Jane Harrison, Ph.D. and Lauren Vorhees, North Carolina Sea Grant, North Carolina State University

2.1 Introduction to onsite wastewater treatment

As climate change drives the rise of sea level, groundwater levels, and storm activity along coastal communities, the need to understand onsite wastewater treatment and how current and future climate impacts their function is more important than ever.

Onsite wastewater treatment systems (OWTS) are used to treat wastewater from individual homes or businesses and return treated wastewater into the nearby soils. Many OWTS are referred to as septic systems because they involve a septic tank for the first stage of treatment. Most OWTS rely on unsaturated soils to complete treatment of the wastewater before it enters surrounding water bodies.

There are various types of systems available. Conventional-style systems are by far the most commonly installed type, which are composed of two primary treatment components: a septic tank and a drainfield where the soil treatment occurs. The septic tank filters out the solid wastes, and the soil particles in the drainfield filter out bacteria and viruses, and facilitate nutrient transformation and treatment, as the sewage percolates through it. Bacteria and viruses in human wastewater can potentially cause disease if transmitted to humans by contact or ingestion. Advanced systems contain those components as well, but also contain additional components to aid treatment, such as disinfecting units and pump systems. Advanced treatment options, which are more costly, are typically only used when the conditions on a property are inadequate for a conventional system.

An alternative option for some communities where individual properties have inadequate site conditions is to build a community or cluster system, also known as package treatment plants (PTPs). These are small wastewater treatment plants that treat wastewater for a cluster of homes, such as a business (e.g. hotel), neighborhood or group of neighborhoods. In this case, each individual home would have pipes and pumps to send the household wastewater to be treated at the PTP. PTPs use a series of tanks and mechanisms to clean the wastewater in the plant before dispersing it into a large drainfield or spray irrigation field, which continues to treat the wastewater as it percolates through the soil, the same as is done in a conventional system. Some PTPs may discharge effluent to surface waters if the effluent is disinfected and the discharge is routinely monitored for water quality characteristics. Cluster systems may also include a group of residences or businesses with individual conventional septic tanks that drain to a community drainfield.

Inadequate conditions for OWTS generally means the soil characteristics (e.g., depth, structure, mineralogy) will not allow for the effective treatment and dispersal of wastewater. This could be caused by wastewater flows that are too large relative the available area for the drainfield, presence of expansive clays that have very low percolation rates, inadequate surface and/or subsurface drainage, or groundwater levels that are too high for wastewater to be treated by percolating through the soil. In the current climate regime, many onsite systems are already at risk of failure[22]. Site conditions in some coastal areas are already undesirable, leading to failing systems and constraining development in new areas. Drainage, soil type, elevation, groundwater height and slope are key to the functionality of OWTS.

[22] Cooper, J. A., G. W. Loomis, J. A. Amador, 2016: Hell and High Water: Diminished Septic System Performance in Coastal Regions Due to Climate Change. *PloS One* 11 (9). doi: https://doi.org/10.1371/journal.pone.0162104

Vertical separation distance beneath systems – the vertical depth of the soil treatment area before it reaches groundwater – is one of the most critical standards for ensuring adequate treatment of wastewater.[23] [24] It is depicted in **Figure 2.1**. In order to properly treat wastewater leaving a septic tank, it's generally accepted that the wastewater needs to travel through *at least* 12 inches (30 cm) of unsaturated soil (aka. vertical separation distance) before entering surrounding water (i.e., groundwater or surface waters). However, more reliable treatment has been shown to occur when several feet of unsaturated soil is available.[25] [26] If sufficient distance is not available, contaminated wastewater containing nitrogen, phosphorus, and fecal coliform bacteria may enter surrounding waters and pose health risks to residents of that area and the environment.

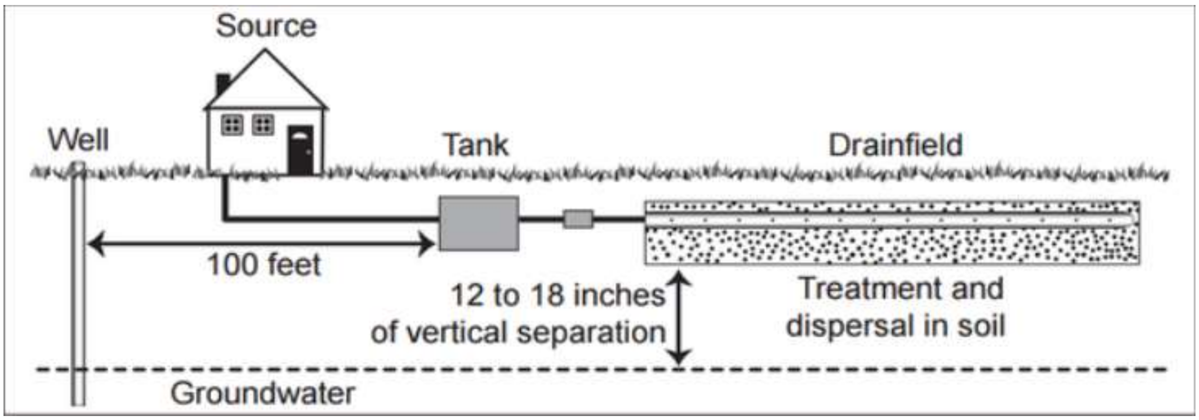


Figure 2.1. Vertical separation distance requirements for conventional systems in North Carolina.[27]

Because most OWTS installed in the coastal Carolinas are conventional-style systems, they depend on the unsaturated soils for treatment of their wastewater. The vertical separation distance requirements set by regulatory agencies is intended to ensure that adequate unsaturated soils are available for treatment over time. Since this is implemented at the time of installation, it may not account for the reductions in vertical separation distance over time in areas with rising groundwater tables. This means that any increase to the groundwater level beneath drainfields and/or sea level near drainfields in these areas could pose a significant threat to the functioning of septic systems there.

2.2 Vulnerability to climate change

Many areas on the East Coast, including North and South Carolina, are experiencing increased frequency and severity of storm events that are threatening OWTS, which tend to be concentrated in low-lying areas

[23] Humphrey C. P., M. A. O'Driscoll, M. A. Zarate, 2011: Evaluation of on-site wastewater system E. coli contributions to shallow groundwater in coastal North Carolina. *Water Science and Technology* 63 (4): 789-795.

[24] Humphrey, C. P., G. Iverson, M. A. O'Driscoll, 2017: Nitrogen Treatment Efficiency of a Large Onsite Wastewater System in Relation to Water Table Dynamics. *Clean Soil Air Water* 45 (12). doi: https://doi-org.prox.lib.ncsu.edu/10.1002/clen.201700551.

[25] Karathanasis A.D., T.G. Mueller, B. Boone, Y.L. Thompson, 2006: Nutrient removal from septic effluents as affected by soil thickness and texture. *Journal of Water Health* 4(2):177-95. PMID: 16813011.

[26] Karathanasis, A.D., T. G. Mueller, B. Boone, Y. L. Thompson, 2006: Effect of soil depth and texture on fecal bacteria removal from septic effluents. *Journal of Water Health* 4(3): 395–404. doi: https://doi.org/10.2166/wh.2006.043.

[27] NC State University Extension. 2014. "Why do septic systems fail?" https://content.ces.ncsu.edu/why-do-septic-systems-fail.

of these states.[28] [29] [30] [31] [32] [33] Between rising sea levels, rising groundwater levels, and more intense and frequent coastal storms from climate change, the vertical separation distance underneath septic drainfields is narrowing or being eliminated completely. This is causing saturation of the soil treatment area beneath OWTS and reduction of treatment capacity. If unsaturated soils are unavailable for onsite wastewater treatment, the systems will malfunction. **Figure 2.2** depicts how the separation distance underneath a drainfield can become compromised with sea level rise, groundwater level rise, and increased rainfall from storm activity.

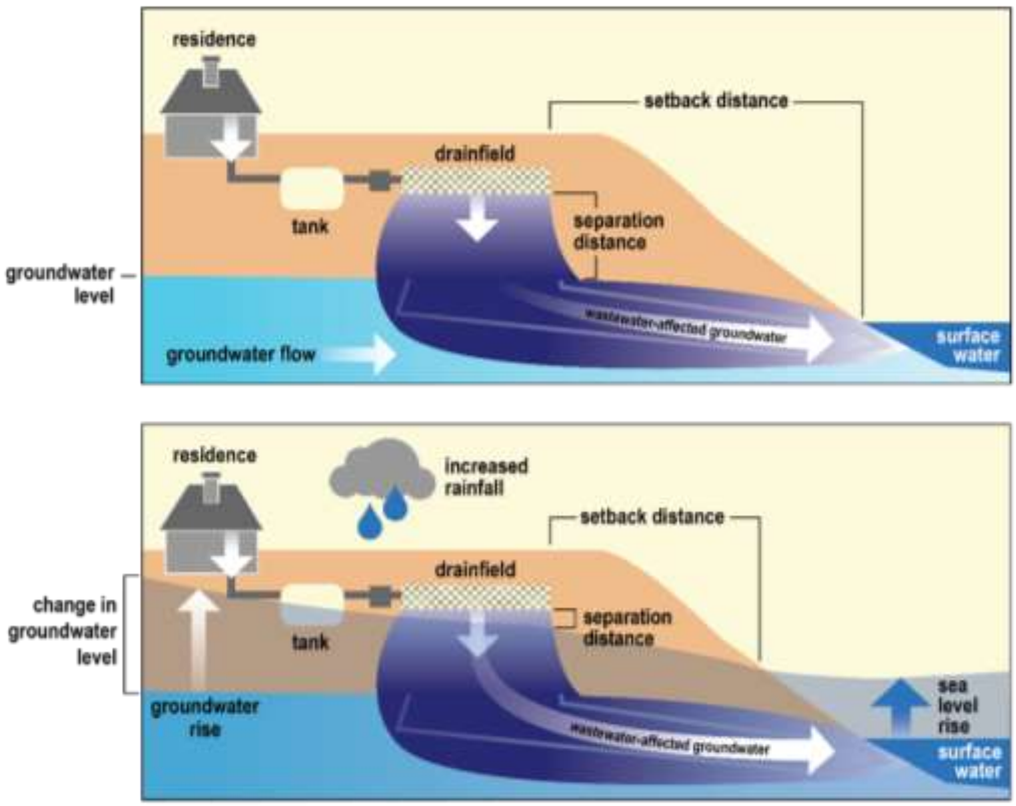


Figure 2.2. How rising sea levels, groundwater levels and increased rainfall reduce the separation distance needed for onsite wastewater treatment. Source: Illustration by Melissa D. Smith[34]

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[28] Allen, T. R., T. Crawford, B. Montz, J. Whitehead, S. Lovelace, A. D. Hanks, A. R. Christensen, and G. D. Kearney, 2018: Linking Water Infrastructure, Public Health, and Sea Level Rise: Integrated Assessment of Flood Resilience in Coastal Cities. Public Works Management & Policy. SAGE Journals.

[29] Cox, A. H., G. W. Loomis, and J. A. Amador, 2019: Preliminary Evidence That Rising Groundwater Tables Threaten Coastal Septic Systems. Journal of Sustainable Water in the Built Environment, 5 (4).

[30] Cox, A. H., M. J. Dowling, G. W. Loomis, S. E. Engelhart, 2020: Geospatial Modeling Suggests Threats from Stormy Seas to Rhode Island's Coastal Septic Systems. Journal of Sustainable Water in the Built Environment, 6 (3).

[31] Hummel, M. A., M. S. Berry, and M. T. Stacey, 2018: Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coast. Earth's Future, 6 (4), 622-633, https://doi.org/10.1002/2017EF000805.

[32] Kunkel, K.E., D.R. Easterling, A. Ballinger, S. Bililign, S.M. Champion, D.R. Corbett, K.D. Dello, J. Dissen, G.M. Lackmann, R.A. Luettich, Jr., L.B. Perry, W.A. Robinson, L.E. Stevens, B.C. Stewart, and A.J. Terando, 2020: North Carolina Climate Science Report. North Carolina Institute for Climate Studies, 233 pp. https://ncics.org/nccsr.

[33] Little, C.M., R.M. Horton, R.E. Kopp, M. Oppenheimer, G.A. Vecchi, and G. Villarini, 2015: Joint projections of US East Coast sea level and storm surge. Nature Climate Change, 5, 1114-1120, https://doi.org/10.1038/nclimate2801.

[34] Vorhees, L., J. Harrison, M. O'Driscoll, C. Humphrey Jr., J. Bowden, 2022: Climate change and onsite wastewater treatment systems in the coastal Carolinas: Perspectives from wastewater managers. *Weather, Climate and Society*. In Press.

In addition to climate change, wastewater systems already suffer from a host of existing problems related to aging infrastructure, as well as being designed to meet outdated environmental or service standards.[35] While all systems require ongoing maintenance, in many cases this is not carried out.[36] Climate change impacts will potentially worsen existing issues with poor-performing or poorly maintained systems.[37]

If the soil in a drainfield is dry before a heavy rainfall event, the system is likely to be able to handle the water from that event. However, if the soils were already saturated before the rain, the additional water could start to cause problems. Inundation that comes from storm surge and/or large precipitation events remains in a drainfield for any length of time will also prevent the system from functioning and could potentially damage the system.

How well a system will fair in a storm or be able to recover afterwards depends on the ability of the drainfield to drain the excess water away from the drainfield quickly. This usually requires permeable soils and an adequate slope on the land that will carry water downgradient from the system. Age and how well a system has been maintained throughout its life are also key factors in how a system will recover. OWTS that are old, have not been well-maintained, or were installed on sites with poor drainage features are highly susceptible to malfunction or even failure when they are inundated with water by a weather event. OWTS can typically tolerate infrequent and brief (a few days) spikes of the water table, causing saturation of the drainfield trenches, but prolonged saturation of that soil results in incomplete treatment of septic effluent.[38]

In the case that an onsite system malfunctions from water inundation, the easiest thing in the short-term is to not use that system for a few days to allow the soils in the drainfield to dry out. But if the system is having chronic problems due to weather events and/or rising groundwater levels, it may be time to look at other options. Long term options include installing an advanced treatment system to replace the conventional-style system or installing an effluent pump to pressure dose septic tank effluent to new drainfield trenches installed in fill material that are elevated above the natural ground surface. However, these options are expensive for homeowners and can cost between $25,000 and $30,000 whereas a conventional-style system generally costs under $10,000. Thus, this technological fix will only be available to those with sufficient financial means. **Table 2.1** displays some examples of advanced system options in the Carolinas.

[35] Hughes, J., K. Cowper-Heays, E. Olesson, R. Bell, A. Stroombergen, 2020: Impacts and implications of climate change on Wastewater Systems: A New Zealand perspective. Climate Risk Management, 31, https://doi.org/10.1016/j.crm.2020.100262.

[36] EPA [United States Environmental Protection Agency], 2002: On-site Wastewater Treatment Systems Manual. EPA/625/R-00/008, United States Environmental Protection Agency, Washington, DC.

[37] Uccellini, L.W. and J. E. Ten Hoeve, 2019: Evolving the National Weather Service to Build a Weather-Ready Nation: Connecting Observations, Forecasts, and Warnings to Decision-Makers through Impact-Based Decision Support Services. Bulletin of the American Meteorological Society, 100 (10), 1923-1942, https://doi.org/10.1175/BAMS-D-18-0159.1.

[38] Severson, E.D., D.L. Lindbo, and M.J. Vepraskas, 2008: Hydropedology of a Coarse-Loamy Catena in the Lower Coastal Plain, NC. Catena, 73 (2), 189-196.

Table 2.1. Advanced system types approved in North and South Carolina.

System type	Description
Aerobic Treatment Unit (ATU)	Oxygen is injected into the septic effluent to increase natural bacterial activity.
Fixed media biofilters	Effluent from the septic tank is treated as it passes over a media filter (e.g., sand, peat, textile, or porous foam) before being diverted to the drainfield for final dispersal.
Constructed wetland system	Effluent flows to a wetland cell where it is treated by microbes, plants, and other media that remove pathogens and nutrients before flowing into a drainfield.
Low-pressure pipe system (LPP)	Effluent enters a pumping chamber, where it is pumped through a series of small diameter pipes to pressure-dose the drainfield.
Drip distribution system	Effluent travels to a distribution box, which Time-doses the delivery of wastewater to the drainfield.
Mound system	Effluent is pumped in prescribed doses into a raised constructed sand mound that contains a drainfield trench where it filters through the sand.

Now, more than ever, coastal communities need to know how rising water levels are affecting their onsite wastewater infrastructure and what strategies can be implemented to ensure adequate wastewater treatment and protect public and environmental health.

3. Coastal groundwater dynamics and their influence on onsite wastewater treatment systems

By Michael O'Driscoll, Ph.D., Dept. of Coastal Studies, Charles Humphrey, Ph.D., Dept. of Health Education & Promotion, and Guy Iverson, Ph.D., Dept. of Health Education & Promotion, East Carolina University

3.1 Groundwater level monitoring

Groundwater level data collected by the N.C. Department of Environmental Quality (NCDEQ) provided the opportunity to evaluate the influence of sea level rise on groundwater levels in Dare County, N.C. Eight sites with wells screened in the surficial aquifer have been monitored since the 1980s and NOAA has been monitoring sea level at Duck, NC since the 1970s (**Figure 3.1**). The longer-term mean annual groundwater depths for the eight Dare Co. surficial aquifer wells suggest that as sea level has risen, the groundwater table has also risen. As part of this project, several additional groundwater monitoring stations were installed throughout the Town of Nags Head to provide further information on short-term groundwater dynamics and the effects of septic systems on groundwater quality. These sites were located at the Bonnett Street Beach Access, Dowdy Park, the Nags Head Municipal Complex, and a residential site in South Nags Head (**Figure 3.1**). In addition, an additional NCDEQ groundwater monitoring well at the Coastal Studies Institute in Wanchese was instrumented to provide information relevant to sites located in coastal estuarine settings. These five sites were instrumented with water level loggers and recorded every 30 minutes.

Figure 3.1. NCDEQ surficial aquifer wells (8 sites) in Dare County, NC (orange squares), additional project sampling wells (green triangles), and the NOAA tidal gage at Duck, NC (purple circle). Map created by Guy Iverson.

3.2 Relationship between land surface elevation and groundwater depth

In Dare County there is a relationship between land surface elevation and mean groundwater (GW) levels, based on surficial aquifer groundwater level data at the 8 NC DEQ and 5 project wells from Nov.2019-Feb 2022. Specifically, higher elevation sites tended to have deeper groundwater and lower elevation sites that are closer to the ocean or sound tended to have shallower groundwater (**Figure 3.2**). However, high dunes along beach sites can result in a deeper water table, such as in the case of the Bonnett Street Beach Access site (BS), despite the close proximity to the ocean. Meanwhile, at some relatively high elevation sites, buried layers of peat and organic soils may impede groundwater flow and result in shallower (perched) groundwater at some locations. In areas where the groundwater table is less than 1.067 m (3.5 ft.) deep (currently or in the future), conventional septic systems are likely to be unsuitable for adequate wastewater treatment, assuming a typical depth of drainfield of approximately 0.61 m (2 ft.) and vertical separation distance of 0.45m. Since there were 2 sites (Wright Memorial (WM) and Wanchese Community Center (WCC), see **Figure 3.3**) that had greater than 2m land surface elevation but had mean groundwater depths of less than 1.067m, this would suggest that some sites < 2.6 m land surface elevation may not meet vertical separation requirements under current groundwater conditions. Overall, the data indicate that conventional septic systems would have reduced treatment capacity at 8 of the 13 settings where wells were located (**Figure 3.3**).

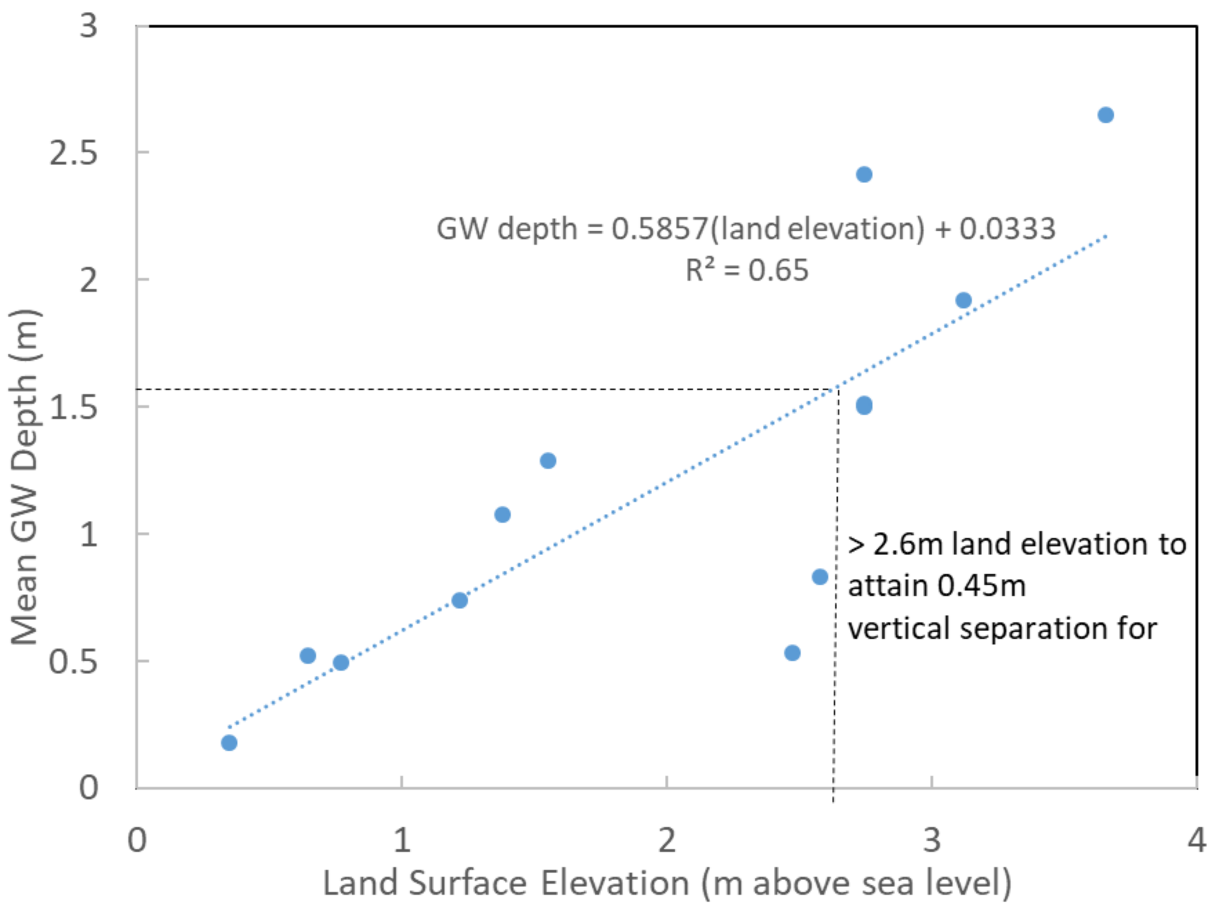

Figure 3.2. General relationship between land surface elevation and GW depth based on average GW depths in NC DEQ groundwater wells and project wells in Dare Co. for the period of Nov.2019-Feb. 2022. Assuming that drainfields are approximately 0.61 m deep, groundwater deeper than 1.067 m would be needed to attain a 0.45m vertical separation for effective soil-based wastewater treatment. Sites that were at land surface elevations of > 2.6 m had GW depths sufficient to meet 45 cm vertical separation between the drainfield and GW table.

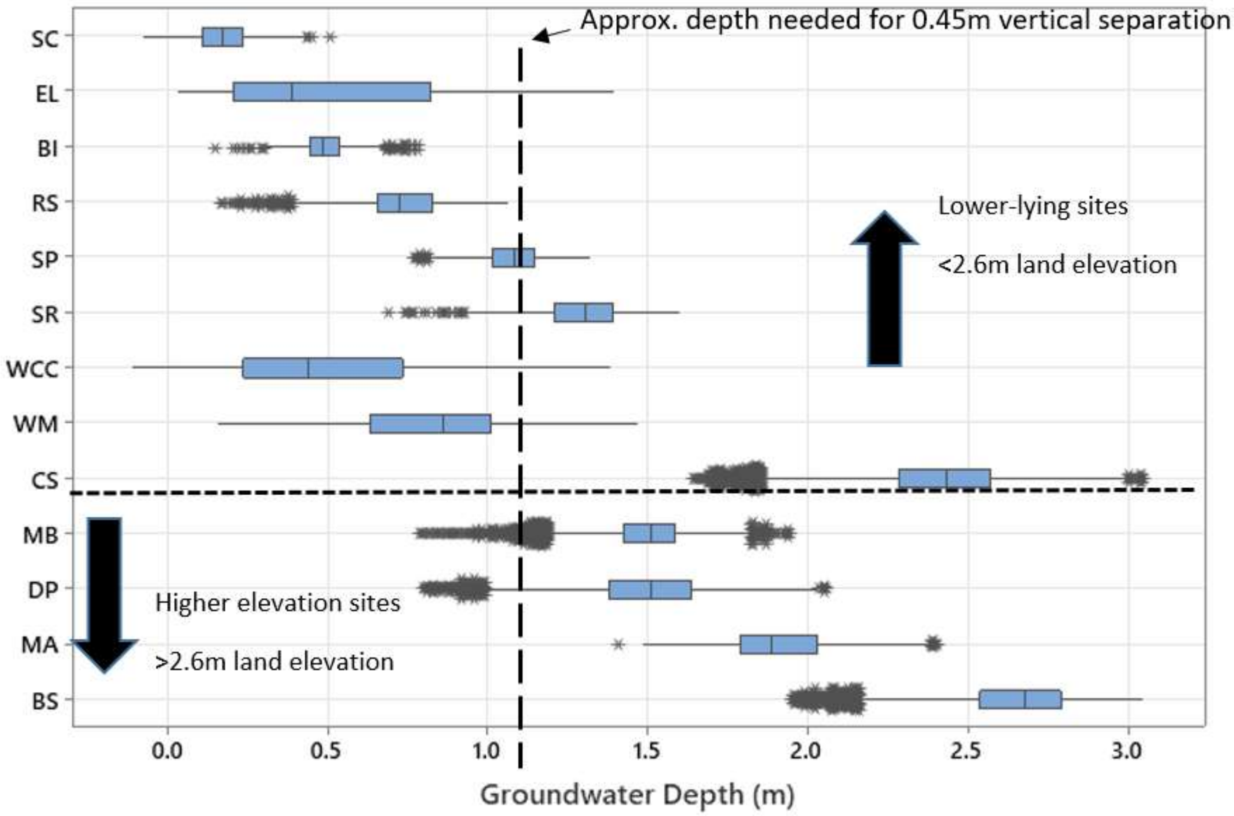

Figure 3.3. Box plots of groundwater depth from Nov. 2019-Feb. 2022 for the surficial aquifer wells. The box plots are arranged in order (from top to bottom) of increasing land surface elevation. Groundwater levels deeper than 1.067m are needed to meet vertical separation of 0.45cm to provide unsaturated soils for effective soil-based wastewater treatment. Note RS, CS, MB, DP, and BS project wells include more shallow outlier values associated with storms because they include data at half-hour increments. i.

3.3 Groundwater level variability

Groundwater levels in Nags Head vary based on the seasonal dynamics of precipitation inputs, evapotranspiration, and ocean and estuary water levels. Typically groundwater depths were shallowest during the winter months, due to lower plant water uptake and cooler temperatures that result in less evapotranspiration (**Figure 3.4**). During these time periods septic systems without adequate separation distance are likely to be less effective than in the warmer months when water table depth is typically deeper. During warm summer months when evapotranspiration was at a maximum the groundwater levels tended to be the deepest. The seasonality associated with evapotranspiration was more pronounced at inland sites, and for sites adjacent to the ocean or estuary, tides had a greater influence on groundwater level variability (**Figure 3.5**). Shorter-term fluctuations of groundwater levels also occurred due to storm events; extreme events caused the groundwater levels to rise several feet and it took weeks to months for these levels to recede, depending on the elevation, type of soil, site drainage, and the size and intensity of the event.

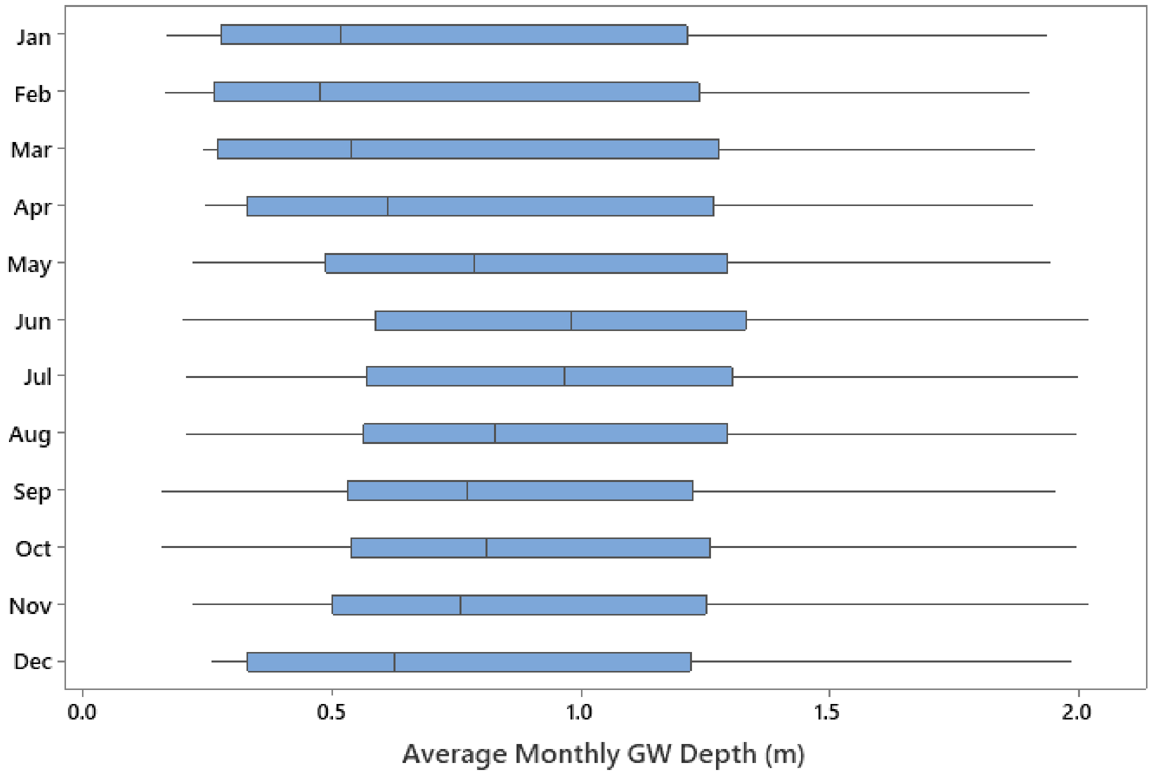

Figure 3.4. Box plots of mean monthly groundwater depth for the eight NC DEQ surficial aquifer wells with long-term data. Groundwater depths tended to be shallower in the winter and deeper in the summer.

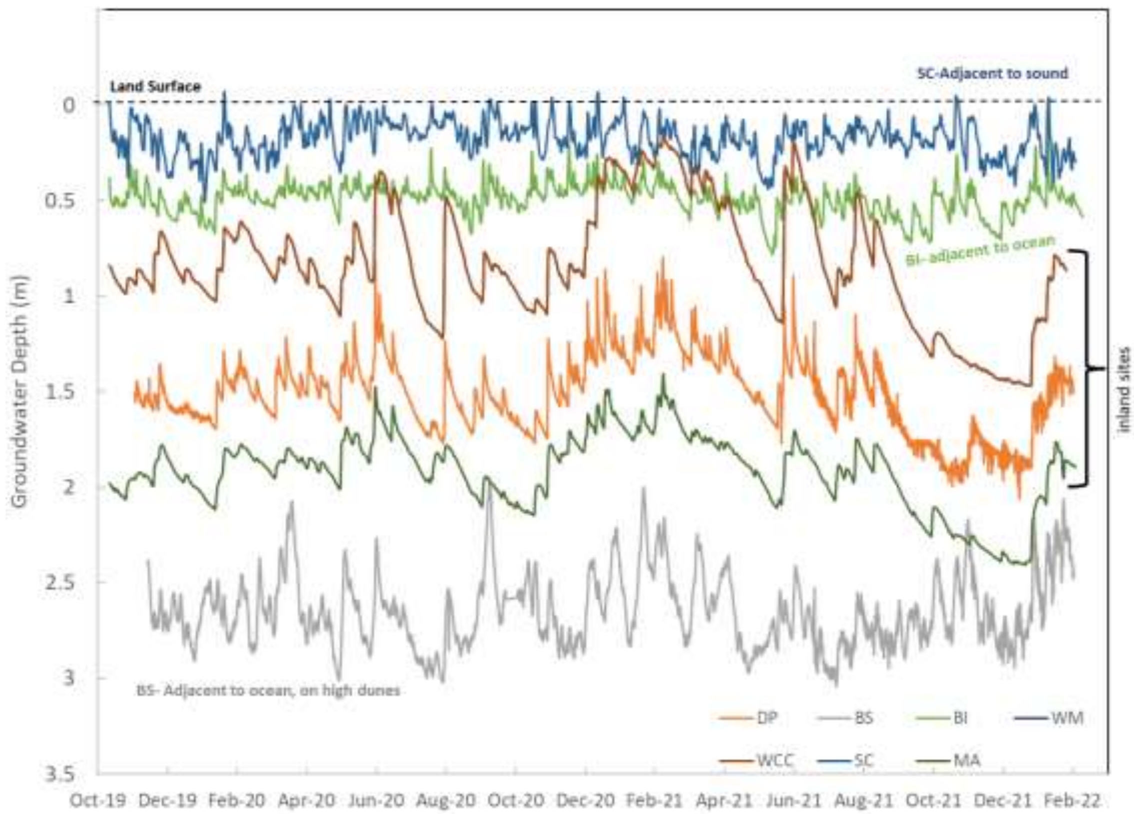

Figure 3.5. Example of surficial aquifer groundwater dynamics observed in Dare Co. wells from Nov. 2019-Feb. 2022. Sites adjacent to the ocean or sound showed variability related to tidal fluctuations, whereas inland sites showed greater seasonal variability associated with the balance between precipitation inputs and evapotranspiration losses. The long-term groundwater depth data showed a common pattern of shallower groundwater depths during winter months associated with reduced evapotranspiration. Inland sites also showed shallower groundwater after large storms and in some cases the recession to pre-storm groundwater levels could take months. At sites with conventional septic systems with shallow groundwater depth, this can mean that it may take several weeks to months for systems to effectively treat wastewater following large storms (> 2 in. or 5 cm.)

In addition, because the water supply is obtained from a deeper confined aquifer (Yorktown aquifer), in Nags Head and Roanoke Island, the surficial aquifer is artificially recharged via onsite wastewater treatment systems. An example is provided from the NCDEQ Wanchese Community Center Well (WCC) nest at Roanoke Island and the Skyco Rd. (SR) well nest adjacent to a community water supply well (**Figure 3.6**). The surficial aquifer is underlain by a confining unit, and the deeper Yorktown aquifer is used for groundwater supplies. Although the groundwater levels are rising in the surficial aquifer and leading to a shallower water table, the groundwater levels in the deeper confined Yorktown aquifer are declining due to water withdrawals. When this water is used in residences and businesses, it is typically discharged to the surficial aquifer via onsite wastewater treatment systems and can contribute to water table rise. In coastal communities that are facing groundwater overdraft issues (e.g. saltwater intrusion, declining hydraulic head, subsidence) in water supply aquifers and rising groundwater levels in the surficial aquifer associated with sea level rise and increased recharge associated with wastewater inputs, potable wastewater reuse could reduce the impacts.[39]

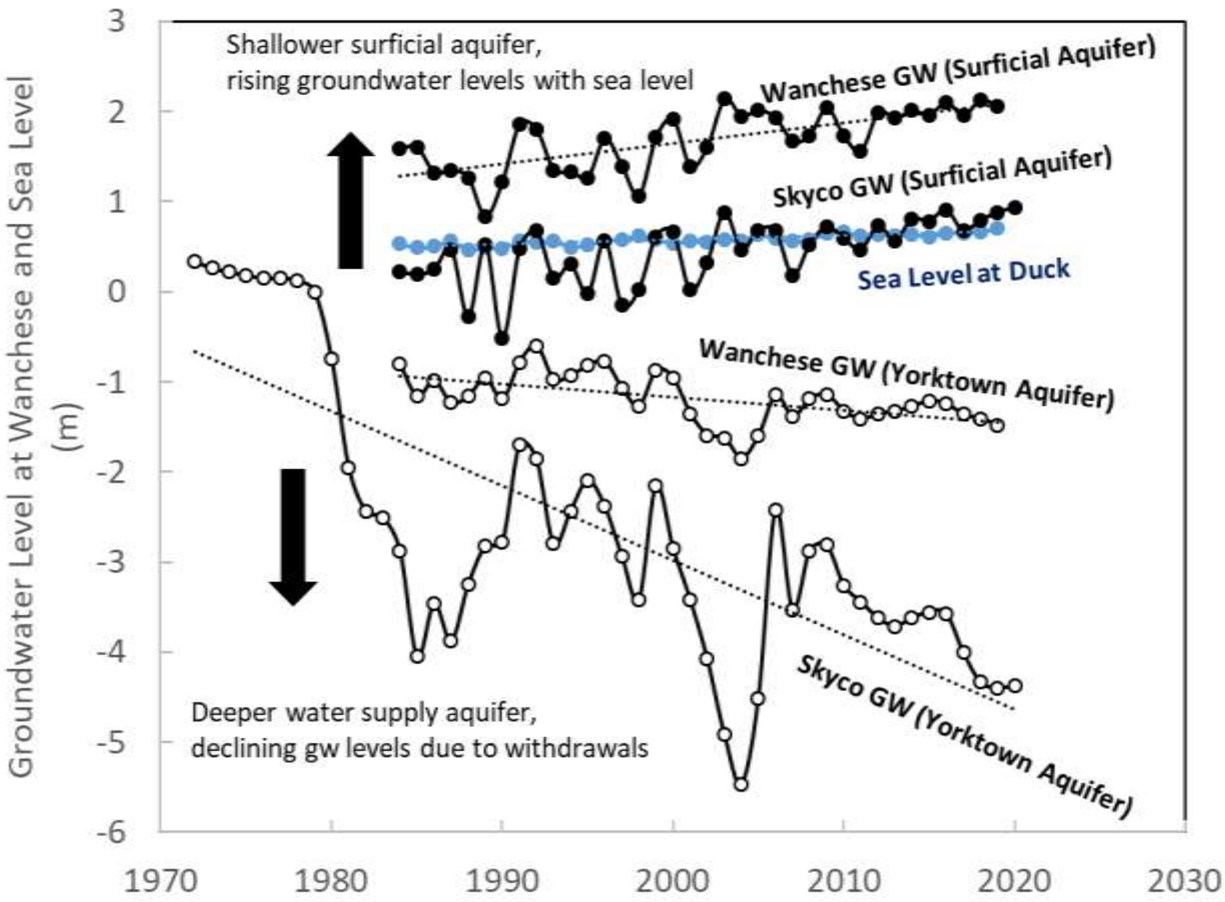

Figure 3.6. Groundwater withdrawals from deeper confined aquifer systems may also contribute to rising groundwater levels in the surficial aquifer if onsite wastewater treatment systems discharge to the surficial aquifer. In this example groundwater withdrawals from the deeper (~61 m or 200 ft.) Yorktown aquifer on Roanoke Island are causing groundwater level declines in the deeper aquifer.

3.4 Sea level rise and groundwater depth

Long-term groundwater and sea level data for Dare County, NC indicates that groundwater levels in the surficial aquifer are rising and surficial aquifer groundwater depth is declining in this area. An analysis of surficial aquifer groundwater levels and sea level rise in Dare County was performed utilizing groundwater and sea level rise data obtained from NCDEQ and NOAA, respectively (**Figure 3.1**). At Duck, North Carolina, NOAA has been monitoring tidal levels since the 1970s. Their records show that sea level at Duck has been rising approximately 4.8 mm/yr or approximately 1.9 inches/decade from 1978-2020 (**Figure 3.7**). A comparison of mean annual groundwater depth for the eight NCDEQ surficial aquifer wells and the mean annual sea level measured at Duck, NC revealed that GW level is rising in the surficial aquifer, and groundwater depths are declining, as sea level rises at the coast (**Figure 3.8**).

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[39] J. Lahnsteiner, P. van Rensburg, J. Esterhuizen; Direct potable reuse – a feasible water management option. Journal of Water Reuse and Desalination 1 March 2018; 8 (1): 14–28. doi: https://doi.org/10.2166/wrd.2017.172.

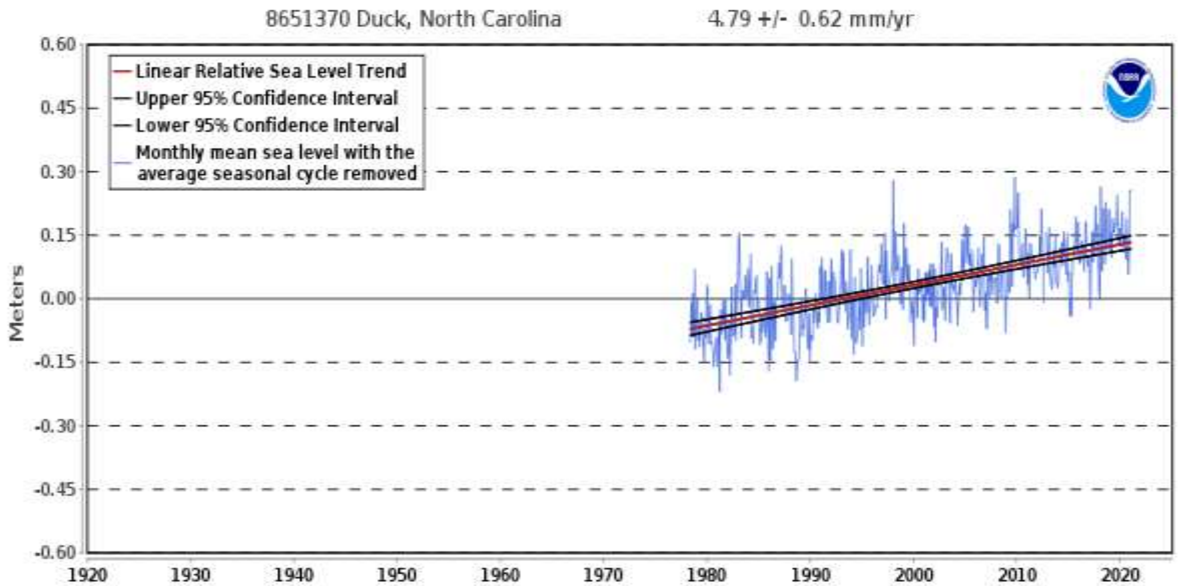

Figure 3.7. Sea level rise measured at the Duck tidal gage for the record from 1978-2020. Data source: NOAA available at: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8651370

This is a broader occurrence that has been observed along the Atlantic Seaboard with evidence of rising groundwater levels noted in various coastal communities in Rhode Island and Florida. [40] [41] [42] The long-term NCDEQ groundwater level data from the 1980s to present suggests that groundwater levels in Dare Co. are rising at a similar or faster rate than the longer term sea level rise at Duck, NC (**Figure 3.8**) (median at 5 sites (BI, MA, SR, SC, and EL) with daily data= 12 mm/yr (range from 6.3-16.8 mm/yr) for 2009-2020 (R^2 values ranged from 80.4-12.3). Similar observations were made by Cox et al. in Rhode Island,[43] and the authors suggested that water use may also play a role. As mentioned earlier, in cases where water is withdrawn from deeper aquifers, such as in Dare Co., and that water is then discharged to the surficial aquifer (the shallowest aquifer at the surface), this may cause groundwater levels to rise more rapidly. It has been shown that in coastal communities that have large increases in summer population associated with tourism, water use and wastewater discharges (and associated groundwater recharge) may be elevated in the summer months. For example, in Bogue Banks, NC, it was estimated that groundwater recharge associated with wastewater inputs could increase the natural groundwater recharge by approximately 20% annually.[44] Deforestation and its influence on evapotranspiration may also play a role.

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[40] Cox, A. H., Loomis, G. W., & Amador, J. A. 2019. Preliminary evidence that rising groundwater tables threaten coastal septic systems. Journal of Sustainable Water in the Built Environment, 5(4), 04019007. https://doi.org/10.1061/JSWBAY.0000887

[41] Miami-Dade County & Florida Department of Health. 2018. Septic systems vulnerable to sea level rise. Available at: https://www.miamidade.gov/green/library/vulnerability-septic-systems-sea-level-rise.pdf

[42] Sukop, M., Rogers, M., Guannel, G., Infanti, J., and Hagemann, K. 2018. High temporal resolution modeling of the impact of rain, tides, and seal level rise on water table flooding in the Arch Creek basin, Miami-Dade County Florida, USA. Science of the Total Environment 616–617: 1668–1688.

[43] Cox, A. H., Loomis, G. W., & Amador, J. A. 2019. Preliminary evidence that rising groundwater tables threaten coastal septic systems. Journal of Sustainable Water in the Built Environment, 5(4), 04019007. https://doi.org/10.1061/JSWBAY.0000887

[44] O'Driscoll, M., Bean, E., Mahoney, R.N., and Humphrey, C. 2019. Coastal tourism and its influence on wastewater nitrogen loading: A barrier island case study. Environmental Management 64: 436–455.

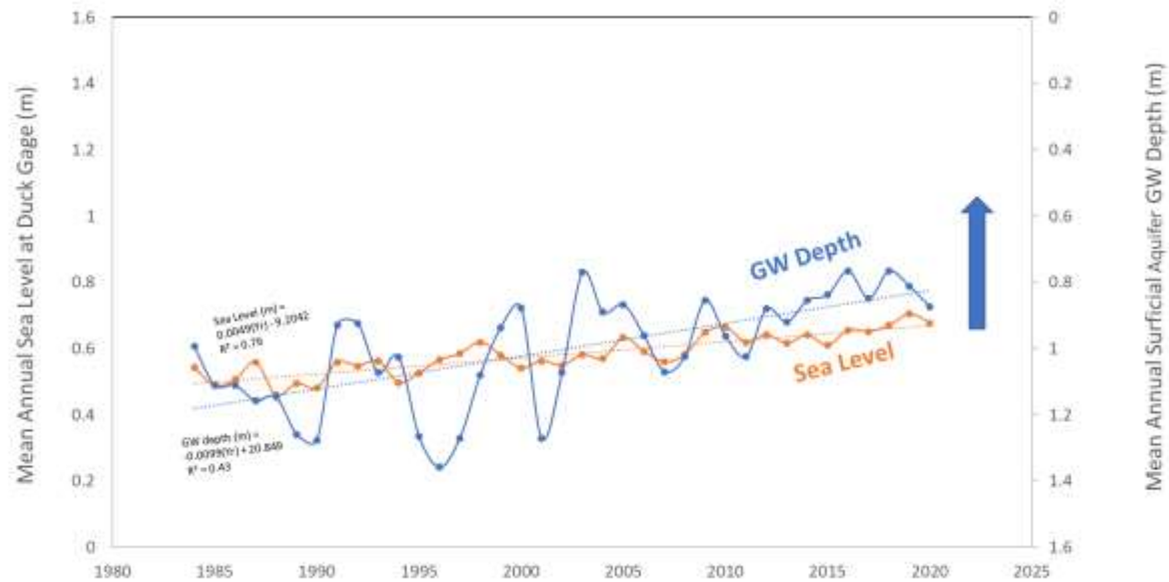

Figure 3.8. Comparison of mean annual sea level at the NOAA Duck, NC tidal gage and mean annual groundwater depth in NC DEQ surficial aquifer wells (8 sites) in Dare County, NC. Note that the groundwater depth axis is inverted (0=land surface and greater depths are to the bottom of the figure). Data sources: NOAA and NC DEQ.

Of the long-term NCDEQ wells screened in the surficial aquifer, one was located in Nags Head, at the Bodie Island (BI) site adjacent to a residential site (RS) that was monitored for groundwater depth and water quality. This allowed us to evaluate long-term trends, as well as evaluate the impacts of rising groundwater on septic systems directly. The groundwater depth data trends over time at the Bodie Island well suggest that groundwater levels have been rising since the 1980s (**Figure 3.9**). The frequency of data collection increased in 2008 and daily groundwater depth and level data has been available since then. These data show that since 2008 there have been at least 3 events where the groundwater levels were above the land surface, suggesting that septic systems in this area and the land surface would have been temporarily inundated. The deep extremes of groundwater depths close to 1m appear less likely over the past decade. The deepest groundwater depth over the period of record was 0.96 m., suggesting that conventional systems in this area that are not mounded would likely not meet the vertical separation distance requirements. When comparing the mean annual groundwater depths at the Bodie Island well for the period of daily data, the data suggest that groundwater levels are rising with sea level at a rate of approximately 6 mm/yr (**Figure 3.10**). Although precipitation may influence seasonal and event variability of groundwater depths, the total annual precipitation was not correlated with mean annual groundwater depth. However, mean annual sea level at Duck explained approximately 53% of the variability in mean annual groundwater depth.

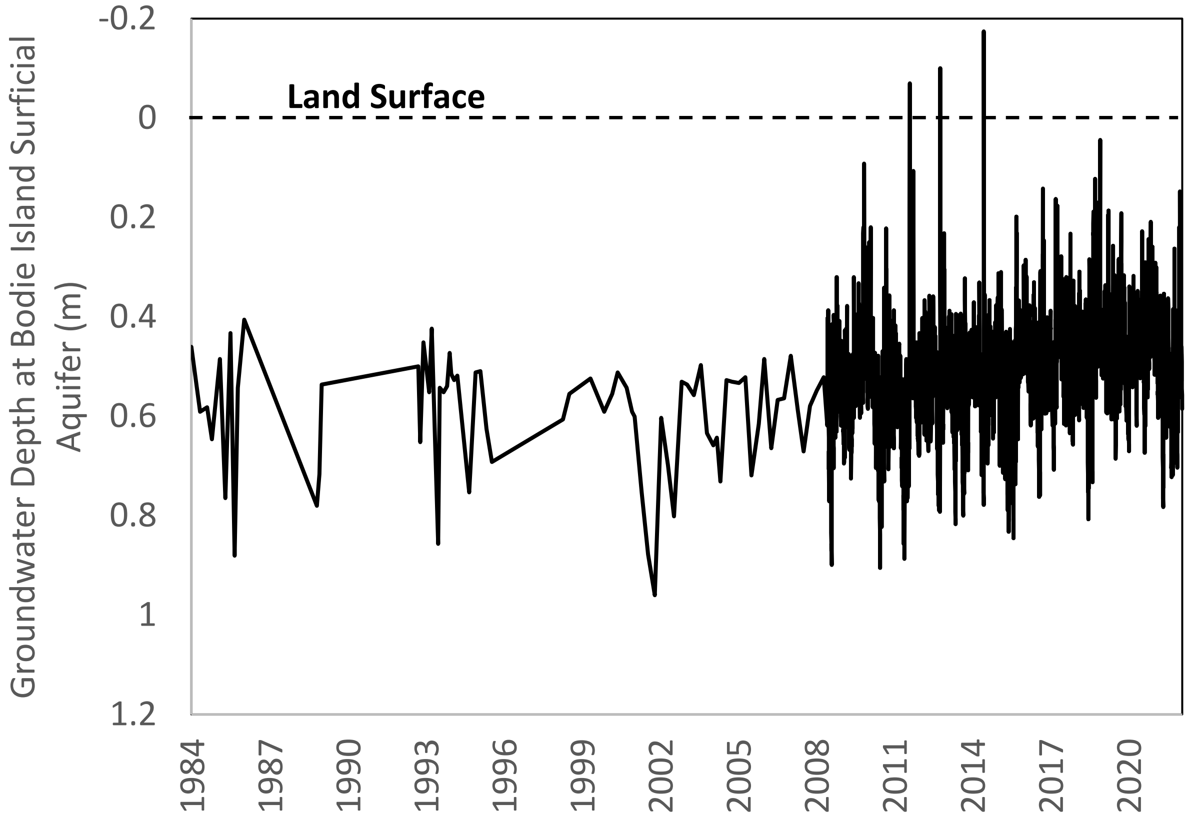

Figure 3.9. Groundwater depths measured in the surficial aquifer at Bodie Island (BI) sites by NC DEQ since 1984. Sampling frequency increased to daily in 2008.

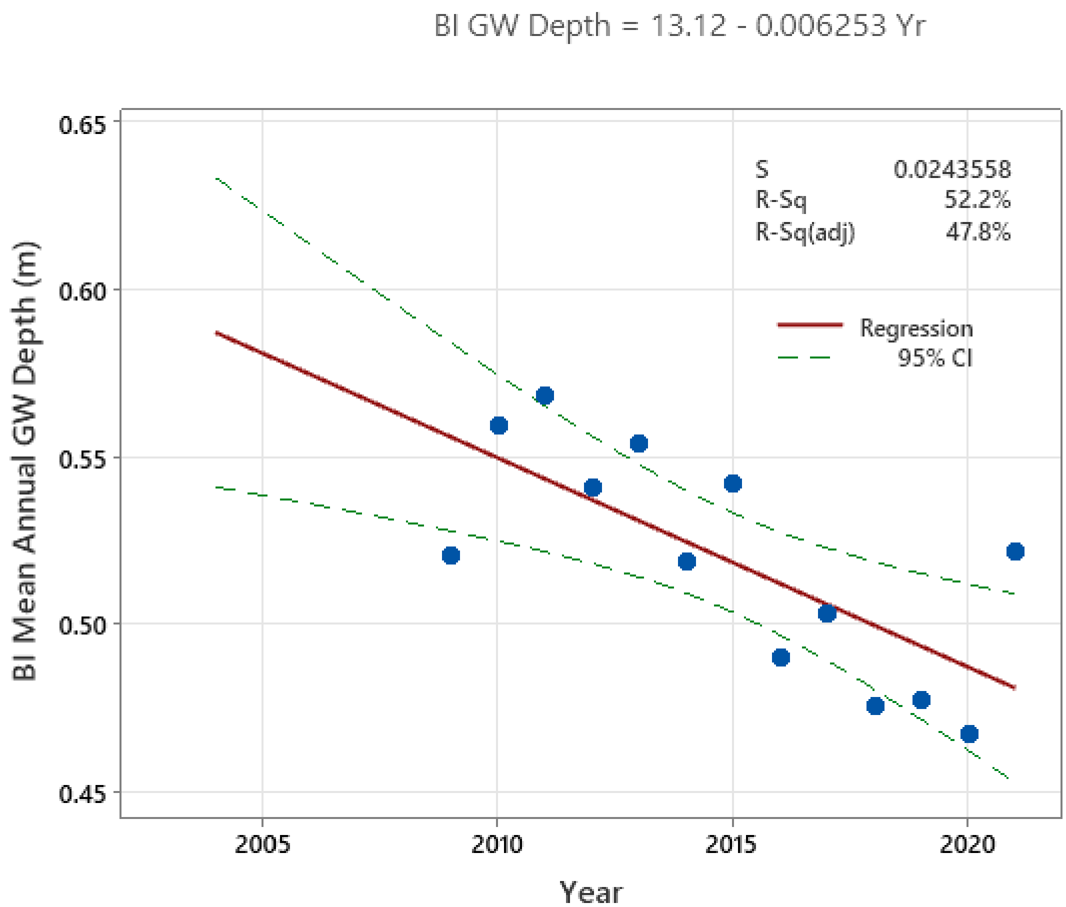

Figure 3.10. Mean annual groundwater depths measured in the surficial aquifer at Bodie Island (BI) based on daily data since 2008 collected by NC DEQ. The trend suggests a 6.3 mm/yr groundwater rise in this area from 2008-2021.

The south Nags Head residential well (RS) was located to the north of the DEQ Bodie Island well and groundwater depths at this site were collected from November 2020- February 2022 on a half-hourly basis. This site also showed shallow groundwater table conditions. During site visits, it was observed that the tank was inundated by groundwater; for example, during a sampling visit in November 2020, we observed the inlet pipe to the tank was inundated **(Figure 3.11)**. At this site, the well was located in the septic system drainfield, so a direct comparison could be made with the drainfield trench depth and groundwater levels. Based on the current record from Nov. 2020-Feb. 2022, the groundwater was in the drainfield trench for approximately 69% of the time (**Figure 3.12**). At this site, groundwater depth would need to be 1.25 m deep to meet the vertical separation distance requirements for sandy soils (0.45m in NC). During the data collection period, the groundwater depth was never greater than 0.3 m below the drainfield trench. These data suggest that systems in these shallow water table settings will not typically have adequate soil-based wastewater treatment, particularly in the winter months or during wet periods.

Figure 3.11. A septic tank in South Nags Head (RS) that was inundated by groundwater in November 2020.

For the future, based on recent trends in groundwater level and sea level rise, approximate estimates for the rise in groundwater levels at the Bodie Island well (6.3 mm/yr) can be used to evaluate future scenarios for the South Nags Head area. An example is provided for the South Nags Head residential site (Figure 3.12). The recently monitored groundwater depths were compared to an approximation for what the groundwater levels would have been like in 1988 when the system was installed. At that time the groundwater levels would have likely been below the drainfield trench for most of the year, except during wet periods. Projecting the observed trend forward to 2050, the data suggest that the drainfield trench will likely be inundated year-round, and during wet periods, the groundwater may rise to the surface at this site and other sites at similar elevation (land surface at approximately 1.2m above sea level). Based on these data, it is likely that there are a large number of systems like this example at similar elevations along the Outer Banks where systems are being inundated by rising groundwater, and it is expected that these systems will not adequately treat wastewater prior to discharge to the shallow groundwater system.

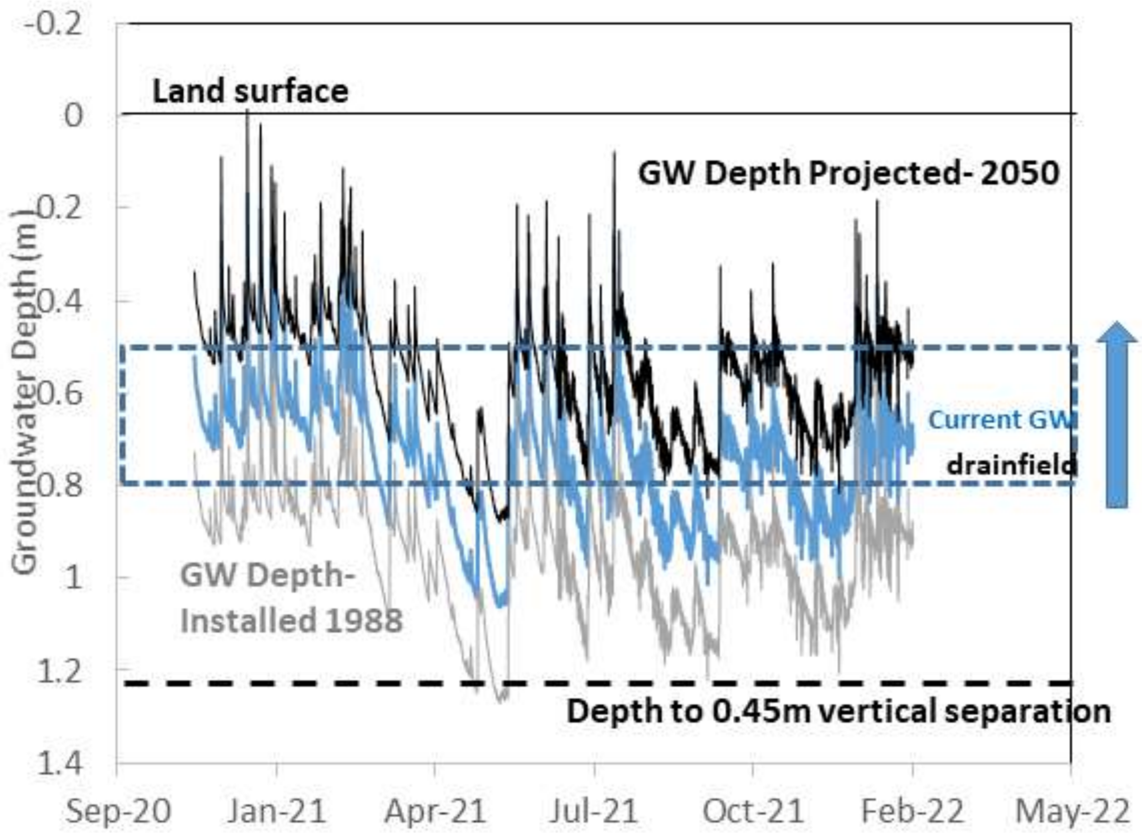

Figure 3.12. The blue line shows groundwater depths at the South Nags Head residential site (RS) for the current monitoring period (Nov. 2020-Feb. 2022). The gray line shows an approximation for what the groundwater levels would have been like in 1988 when the system was installed (based on the recent groundwater level rise trend of 0.63 cm/yr. estimated at the Bodie Island well based on daily data from 2009-2021). The black line shows what the groundwater levels may be like in 2050 based on the recent rates of groundwater level rise in the area, with an increased likelihood of wastewater-affected groundwater upwelling at the land surface.

4. Evaluation of wastewater treatment system effectiveness

By Charles Humphrey, Ph.D., Dept. of Health Education & Promotion, Michael O'Driscoll, Ph.D., Dept. of Coastal Studies, and Guy Iverson, Ph.D., Dept. of Health Education & Promotion, East Carolina University

4.1 Wastewater treatment technologies and processes

Wastewater contains many pollutants that pose environmental and public health risks if their concentrations are not reduced before release to water resources (e.g., groundwater, lakes, streams, estuaries). Examples of pollutants in wastewater that often cause environmental health concerns such as impairment of water resources include nitrogen, phosphorus, and bacteria.[45] Excess nitrogen and phosphorus loading to coastal waters has been shown to stimulate algal blooms,[46] some of which produce toxins that are harmful to humans and animals.[47] When the algae eventually die and decompose, dissolved oxygen in the water is depleted which may lead to fish kills and unpleasant odors.[48] Wastewater also contains pathogens including bacteria that can cause infections, gastrointestinal issues and other severe illnesses if humans consume the water[49] or have open wounds and come into contact with improperly treated waste.[50] Elevated concentrations of indicator bacteria in coastal waters may trigger swimming advisories and closure of shellfish waters. Water-based tourism and recreational and commercial fishing is a large part of the economy for many coastal communities, so prolonged water quality issues can hurt economic sustainability.[51]

Wastewater is typically treated by either centralized or decentralized technologies. Centralized technologies such as municipal sewer and package treatment plants receive wastewater from cities, towns, housing developments and/or condominiums via collection networks (e.g., pipes and lift stations). Wastewater is piped from many sources to one location where it is treated and discharged, often to receiving bodies of water. In contrast, decentralized technologies including OWTS, often treat and discharge wastewater in the subsurface on the same property from which the waste is generated.

As mentioned previously, most of the wastewater treatment for OWTS occurs in soil beneath the drainfield trenches. Different processes in soil are responsible for reducing nitrogen, phosphorus, and bacteria concentrations. For example, nitrogen removal may occur via several steps that result in the loss of nitrogen to the atmosphere as a gas. First, organic nitrogen is anaerobically digested and mineralized to ammonium (NH_4^+) in the septic tank, a process called ammonification. Septic tank effluent is piped to the drainfield trenches where NH_4^+ is oxidized to NO_3^- (nitrification) if the vertical separation to

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[45] US EPA. Source Water Protection (SWP): Common Considerations. 2022. Available online: https://www.epa.gov/sourcewaterprotection/common-considerations

[46] Mallin, M.A.; McIver, M.R. Pollutant impacts to Cape Hatteras National Seashore from urban runo and septic leachate. Mar. Pollut. Bull. 2012, 64, 1356–1366.

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[48] Mallin, M.A.; Cahoon, L.B.; Toothman, B.R.; Parsons, D.C.; McIver, M.R.; Ortwine, M.L.; Harrington, R.N. Impacts of a raw sewage spill on water and sediment quality in an urbanized estuary. Mar. Pollut. Bull. 2007, 54, 81–88.

[49] Borchardt, M. A., Po-Huang, C., DeVries, E. O. & Belongia, E. A. 2003. Septic system density and infectious diarrhea in a defined population of children. Environmental Health Perspectives 111 (5), 742–748.

[50] US EPA. RecreationalWater Quality Criteria and Methods. 2012. Available online: https://www.epa.gov/wqc/recreational-water-quality-criteria-and-methods.

[51] Singh, S., Bhat, J.A., Shah, S., Pala, N.A. 2021. Coastal resource management and tourism development in Fiji Islands: a conservation challenge. Environment, Development and Sustainability 23, 3009-3027. https://doi.org/10.1007/s10668-020-00764-4.

groundwater and oxygen concentrations in soil pores enable aerobic microbial activity. Denitrification is when NO_3^- is converted to N_2 or N_2O gas, and that process requires anaerobic conditions and organic matter in the soil within the flow path of the infiltrating wastewater. Therefore, there must be alternating aerobic and anaerobic conditions in soil beneath the drainfield trenches for nitrogen to be removed through the nitrification and denitrification steps.[52] The treatment efficiency of nitrogen by OWTS in different soils can be highly variable based on the environmental conditions (e.g., separation distance, soil texture, organic matter content) beneath the drainfield trenches.

Phosphorus removal in soil is often related to adsorption and/or mineral precipitation.[53] Adsorption is when phosphate (PO_4-P) binds to soil particles because of differences in the charge between a PO_4-P molecule and soil. Soils with an abundance of iron and aluminum oxides, and higher clay content with low pH typically have excellent phosphorus adsorption capacity. Sandy soils that do not contain iron and aluminum oxides will be less effective at PO_4-P adsorption. Under certain pH and environmental conditions, PO_4-P may combine with iron, aluminum, or calcium to form a mineral that precipitates out of the soil solution, thus preventing transport of PO_4-P to groundwater. Therefore, soil type, abundance of iron and aluminum oxides, presences of iron, aluminum, and calcium in the soil solution and environmental conditions (pH, redox potential) are some of the main factors that influence phosphorus removal by OWTS. Nitrogen and phosphorus are both essential nutrients for living organisms, and so uptake of inorganic forms of nitrogen (NH_4^+, NO_3^-) and phosphorus (PO_4^-) by plants growing near the trenches and soil microorganisms is another mechanism for nutrient removal in the drainfield.

Pathogens in wastewater can be removed through several processes. As effluent infiltrates soil beneath the drainfield trenches, wastewater is initially drawn into the smallest pores due to capillarity. Bacteria can be physically filtered if their diameter is greater than the diameter of soil pores they are traveling through.[54] Bacteria transport through soil may also be reduced via adsorption to soil particles, or adhesion, a more permanent removal mechanism.[55] Most bacteria in wastewater are anaerobic and thus when exposed to oxic conditions in soil and/or the trenches may die off or be outcompeted with aerobic microorganisms for needed resources.[56] Bacteria in wastewater may also be removed by consumption as a food source for predators in soil. Most of these mechanisms for bacteria treatment are also dependent upon adequate vertical separation to groundwater and aerobic conditions.

In contrast to OWTS, package treatment plants and centralized sewer systems typically treat large volumes of wastewater and employ engineered, active treatment processes that oxidize, filter, and disinfect wastewater. Many package plants and sewer systems use similar techniques and components for wastewater treatment with the main difference between the two being the flow capacity. Package plants typically treat up to 0.5 million gallons per day (0.19 million liters per day), while sewer systems exceed that flow. Some package plant technologies are also used for individual home sites or small

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[53] Robertson WD, Schiff SL, Ptacek CJ (1998) Review of phosphate mobility and persistence in 10 septic system plumes. Groundw 3:1000–1010.

[54] Lusk, M.G.; Toor, G.S.; Yang, Y.-Y.; Mechtensimer, S.; De, M.; Obreza, T.A. 2017. A review of the fate and transport of nitrogen, phosphorus, pathogens, and trace organic chemicals in septic systems. Crit. Rev. Environ. Sci. Technol. 47: 455–541.

[55] Stevik, T.K., Aa, K., Ausland, G., Hanssen, J.F. 2004. Retention and removal of pathogenic bacteria in wastewater percolating through porous media: a review. Water Research 38, 1355-1367. doi:10.1016/j.watres.2003.12.024.

[56] Pang, L., Close, M., Goltz, M., Sinton, L., Davies, H., Hall, C. & Stanton, G. 2003 Estimation of septic tank setback distances based on transport of E. coli and F-RNA phages. Environment International 29, 907–921.

businesses. Most centralized sewer plants and many package plants discharge treated effluent directly to surface waters and thus must maintain a national pollution discharge elimination systems (NPDES) permit. The permit requires routine monitoring and reporting of effluent concentrations and flows. Because of this monitoring requirement, there is generally more information available to resource managers and regulatory officials regarding the efficiency of these wastewater treatment options relative to OWTS. OWTS are considered non-point sources of pollution, and most do not require monitoring for treatment efficiency.

4.2 Monitoring for wastewater treatment efficiency determination

To gain a better understanding of the nitrogen, phosphorus, and bacteria treatment efficiency of OWTS in the coastal Carolinas, 8 OWTS were monitored during this project. The OWTS included conventional-style, gravity flow (BS, FB, RS), pump to conventional-style (JW, OAK), and low-pressure pipe systems (DP, MB, WC). Treatment efficiencies of the OWTS were compared to alternative methods of wastewater treatment including package plants (n = 3) and municipal sewer systems (n = 2) also in the coastal Carolinas. The package treatment plants included CS which uses an *Amphidrome* biological aerated filter, VB which uses an oxidation ditch and activated sludge, and JC which uses aeration ponds and a sand filter prior to land application of effluent. The centralized sewer systems both use biological nutrient reducing technologies with sand filtration. Additional system information is shown in **Table 4.3**.

Wells for groundwater monitoring were installed near the drainfield trenches of the eight OWTS (**Figure 4.1**). Wastewater samples from the septic tanks and groundwater samples from the wells near the drainfield were collected for nutrient and bacteria analyses (**Figure 4.1**). The concentrations of nutrients and bacteria in wastewater were compared to concentrations in groundwater to determine how effective the OWTS were in lowering pollutant concentrations. Prior to sampling, depth to groundwater and vertical separation from drainfield trenches to groundwater were determined at each OWTS site, along with other physical and chemical properties including pH and oxidation reduction potential. The treatment efficiencies of the package treatment plants and centralized sewer systems were estimated by comparing influent and effluent concentrations of nutrients and bacteria. Samples from the sites were collected between 8 and 11 times and twice each season for most locations. Additionally, to estimate mass removal of nitrogen and phosphorus by most OWTS, the nutrient to chloride ratios of wastewater and groundwater near the drainfield were compared.[57] It was assumed that for the package treatment plants and sewer systems the concentration reductions and mass reductions of nutrients were identical.

Table 4.3. Characteristics of monitored wastewater systems including system type and construction date.

Site	Location	Decentralized System Type	Construction Date
BS	Nags Head, NC	Conventional, gravel	2018
RS	Nags Head, NC	Conventional, gravel	1988
FB	Folly Beach, SC	Conventional, gravel	2018
JWS	Cove City, NC	Pump to conventional, gravel	1987
OAK	Greenville, NC	Pump to conventional, polystyrene	2001
DP	Nags Head, NC	Low pressure pipe, gravel	2019

[57] Humphrey, C., Serozi, B., Iverson, G., Jernigan, J., Pradhan, S., O'Driscoll, M., Bean, E. (2016). Phosphate treatment by onsite wastewater systems in nutrient sensitive watersheds of North Carolina's Piedmont. *Water Science and Technology* 74 (7) 1527-1538.

MB	Nags Head, NC	Low pressure pipe, gravel	1997
WC	Vanceboro, NC	Low pressure pipe, gravel	1997

Site		Centralized System Type	Construction Date
VB	Vanceboro, NC	Package plant, oxidation ditch, UV disinfection	1991
CS	Wanchese, NC	Package plant, biological aerated filter, UV disinfection	2012
JC	James City, NC	Package plant, aeration basin, UV disinfection, land application	1985
NB	New Bern, NC	Sewer, biological nutrient removal, sand filter, UV disinfection	1964
GV	Greenville, NC	Sewer, biological nutrient removal, sand filter, UV disinfection	1985

Figure 4.1. Wells were installed near the drainfield trenches of each OWTS. Groundwater samples from the wells and wastewater samples from the septic tanks were collected, analyzed for nutrient and bacteria concentrations and compared to assess treatment efficiency.

4.3 Nitrogen treatment

Overall, the centralized sewer systems had the highest efficiency with regards to Total Dissolved Nitrogen (TDN) concentration reductions (83.7%) followed by OWTS (62.5%) and package treatment plants (47.9%). Nitrogen treatment efficiencies were highly variable for the OWTS and package plants likely because of differences in site conditions, system components, and wastewater strength. For example, OWTS reduced TDN concentrations by between 0 and 95.2% while package plant TDN efficiencies were between 23.5% and 78.9%. Centralized sewer TDN treatment efficiencies were the least variable with a range from 81.6 to 85.8% (**Figure 4.2**), possibly because they employ the same treatment steps. The OWTS at RS was a conventional, gravity-flow system and was the least efficient of all technologies monitored (0%). Groundwater was within the drainfield trenches during each sampling event (**Table 4.4**) and thus there was no separation distance to the water table at the RS site. Septic tank effluent was mixing directly with groundwater. During several field visits wastewater levels in the septic tank were above the top of the inlet pipe, indicating wastewater backup, likely due to a shallow water table and groundwater in the tank. The most efficient OWTS for TDN concentration reduction was BS, also a conventional, gravity-flow system but with a mean separation distance of 5.7 ft (1.74 m) to groundwater (Table 4.4). FB, another conventional, gravity-flow system with a mean separation to groundwater of 5.9 ft (1.8 m) was also relatively efficient (79.7%) ranking 3rd amongst all OWTS. If RS is excluded from this subgroup of OWTS due to groundwater inundation of the trenches, then the gravity-flow, conventional style OWTS were the most efficient (mean of 87.5%) of all wastewater treatment systems (including centralized sewer) with regards to TDN concentration reductions. OWTS sites with LPP systems had mean TDN treatment efficiencies of 71.3%, and efficiencies within this subgroup ranged from 64.7% (WC) to 80.7% (DP). More than 82% of the TDN in groundwater beneath the LPP systems was NO_3^- and the mean separation distance to groundwater for the sites was more than 2 ft (0.6 m), thus the OWTS were effective at oxidizing the wastewater. The least efficient subset of OWTS were the pump to conventional-style systems (JW and OAK) that reduced TDN concentrations by a mean of 55.7%. These OWTS had mean vertical separation distances of 14.7 ft (4.48 m) and 3.5 ft (1.1 m) respectively, and most (> 79%) of the TDN in groundwater beneath the systems was NO_3^-. These systems were well aerated thus enabling nitrification, but nitrogen removal via denitrification was limited. Denitrification is often inhibited by a lack of sufficient carbon in soil beneath drainfield trenches.[58] The carbon is used as an energy source for denitrifying microorganisms.

Prior research has suggested that gravity-flow systems may be more effective at nutrient treatment relative to dosing systems like pump to conventional and LPP because of the development of a biologically active mat (biomat) comprised of microbes, microbial secretions, and small solids that pass through the tank effluent filter and into the drainfield trenches.[59] [60] The biomat gradually thickens along the trench bottom near the front of the trenches, where wastewater first enters the trench. The biomat partially clogs soil pores, reducing the infiltration rate of wastewater into soil, forcing wastewater to move further along the trench to infiltrate in unclogged portions. The biomat extends towards the end of the trenches over time and may increase treatment efficiency. OWTS that use pumps typically dose wastewater to the drainfield trenches a few times per day resulting in wetting periods when the pump is activated and drying periods between doses. The drying periods enable oxidation of organic matter which reduces the rate of biomat formation, potentially resulting in less treatment relative to an OWTS with an active biomat.[61] So, differences in separation distance, biomat formation, carbon availability in the subsoil, and system technology may have been factors that influenced TDN treatment by OWTS.

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Water Res 43:2739–2749.

[61] Bunnell, J.; Zampella, R.; Morgan, M.; Gray, D. A comparison of nitrogen removal by subsurface pressure dosing and standard septic systems in sandy soils. J. Environ. Manag. **1999**, 56, 209–219.

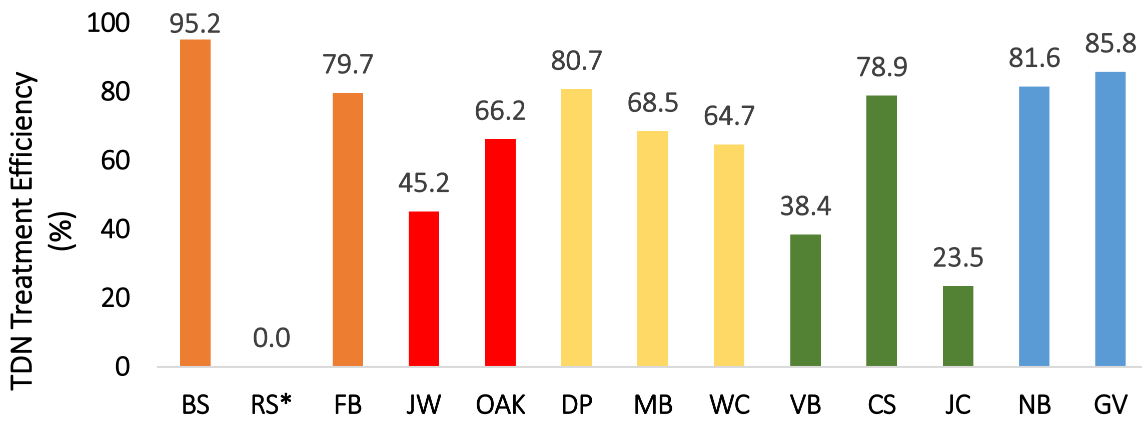

Figure 4.2. Total dissolved nitrogen (TDN) treatment efficiency for each monitored technology based upon differences in median concentrations in wastewater/influent and groundwater/effluent. Orange indicates gravity-flow conventional systems, red are pump to conventional, yellow are low-pressure pipe, green are package plants and blue are centralized sewer sites.

Table 4.4. Concentrations of total dissolved nitrogen (TDN) in wastewater sampled from the septic tanks and groundwater near the drainfield trenches of the onsite wastewater systems, and from influent and effluent at the centralized wastewater systems.

		Wastewater TDN (mg L^{-1})			Groundwater TDN (mg L^{-1})			
Site	**System Type**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Efficiency**
BS	Gravity, Conv.	210.17	147.25	235.34	10.15	1.94	92.39	95.2
RS*	Gravity, Conv.	63.21	38.64	74.27	63.21	38.64	74.27	0.0
FB	Gravity, Conv.	157.1	156.9	157.3	31.94	5.33	143.86	79.7
JWS	Pump, Conv.	50.46	14.84	91.7	27.66	12.55	64.33	45.2
OAK	Pump, Conv.	62.28	22.66	95.32	21.06	6.11	65.18	66.2
DP	LPP	208.96	37.79	277.36	40.27	3.47	82.06	80.7
MB	LPP	96.33	58.06	111.72	30.32	16.23	78.44	68.5
WC	LPP	23.42	3.94	83.48	8.27	0.92	81.99	64.7

		Influent TDN (mg L^{-1})			Effluent TDN (mg L^{-1})			
Site	**System Type**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Efficiency**
VB	Package Plant	21.77	3.95	41.74	13.4	7.64	26.54	38.4
CS	Package Plant	53.64	25.07	95.35	11.33	2.64	22.06	78.9
JC	Package Plant	46.53	17.9	57.13	35.6	19.35	72.19	23.5
NB	Sewer	23.8	17.0	31.05	4.39	1.98	25.08	81.6
GV	Sewer	23.84	14.59	32.86	3.39	0.86	7.82	85.8

The JC package plant only reduced concentrations of TDN by 23.5%, however, this system does not discharge effluent to surface waters, but rather effluent is land applied. Therefore, additional treatment should occur prior to effluent reaching natural waters. If JC is excluded from the group then the average treatment efficiency of the package plants would be 58.7%, and package plants would still be the least efficient at TDN treatment of the main wastewater treatment approaches behind centralized sewer systems (83.7%) and OWTS (62.5%). The CS package plant utilizes a biological aerated filter that includes recirculation of filter effluent and intermittent aeration and resting cycles. The CS package plant was much more efficient (78.9%) than the VB package plant (38.4%) which uses an oxidation ditch with resting and aeration cycles. The median concentration of TDN in effluent discharged by the package plants in this study (13.4 mg L^{-1}) was just below the TDN concentration in effluent (16.7 mg L^{-1}) discharged from 42 advanced treatment systems in Rhode Island[62], and just above the median TDN in effluent discharged from 7 package plants on the outer banks of North Carolina (10.7 mgL^{-1}).[63] The sewer systems at NB and GV both use biological nutrient removal including alternating aerobic and anaerobic stages, with a sand filter polishing process. Treatment efficiencies were relatively high and consistent for the centralized sewer systems (> 81%). The median effluent concentrations of TDN were relatively low for GV 3.39 mg L^{-1} and NB 4.39 mg L^{-1} in comparison to the other treatment technologies. The TDN concentrations discharged by the sewer plants in this study were within the range of effluent concentrations (1.6 – 5.3 mg L^{-1}) reported by Oakley et al.,[64] from 15 centralized sewer plants operating in the US and Canada.

Table 4.5. Physical and chemical properties of wastewater and groundwater sampled from the sites with onsite wastewater systems including oxidation reduction potential (ORP), specific conductance (SC), percentage of total nitrogen that was organic and ammonium (TKN) and percentage of total nitrogen that was nitrate (NO3).

Site	System Type	Depth to Water (ft) Avg (min-max)	Vertical Separation (ft) Avg (min-max)	pH Mean (STDEV)	ORP Mean (STDEV)	SC (uS/cm) Mean (STDEV)	%TKN	%NO3
BS-T				7.9 (0.5)	-151 (137)	2799 (863)	99.8	0.2
BS-DF	Gravity, Conv.	8.2 (6.2 - 9.2)	5.7 (3.7 - 6.7)	6.9 (0.5)	6 (75)	751 (511)	7.9	92.1
RS-T				7.1 (0.7)	-143 (34)	1067 (16)	99.7	0.3
RS-DF	Gravity, Conv.	2.6 (2.0 - 2.8)	0 (0 - 0.2)	7.2 (0.4)	-37 (33)	455 (241)	99.8	0.2
FB-T				7.3 (0.3)	-522 (11)	1632 (11)	99.9	0.1
FB-DF	Gravity, Conv.	8.4 (7.9 - 10.7)	5.9 (5.4 - 8.3)	6.3 (0.3)	54 (32)	743 (376)	26.4	73.6
JWS-T				7.2 (0.2)	-135 (106)	1068 (425)	99.8	0.2
JWS-DF	Pump, Conv.	16.7 (13.1 - 21.8)	14.7 (11.0 - 19.7)	6.3 (0.5)	80 (85)	719 (276)	12.7	87.3
OAK-T				6.9 (0.6)	-184 (75)	823 (241)	99.9	0.1
OAK-DF	Pump, Conv.	5.6 (2.3 - 8.7)	3.5 (0.4 - 6.8)	3.7 (0.6)	126 (98)	270 (86)	20.9	79.1
DP-Tank				8.1 (0.5)	-194 (49)	2660 (1117)	98.7	1.3
DP-DF	LPP	4.7 (3.3 - 5.4)	2.4 (1.1 - 3.2)	6.2 (0.5)	49 (96)	782 (370)	17.3	82.7
MB-Tank				7.6 (0.4)	-181 (59)	1554 (447)	99.8	0.2
MB-DF	LPP	4.7 (3.9 - 5.3)	2.9 (2.1 - 3.5)	7.1 (0.5)	41 (139)	952 (439)	3.2	96.8
WC-Tank				7.2 (0.5)	-139 (93)	678 (306)	99.3	0.7
WC-DF	LPP	5.5 (3.4 - 7.3)	3.7 (1.6 - 5.5)	6.2 (0.4)	7 (78)	330 (255)	8.2	91.8

[62] Lancellotti, B.; Loomis, G.; Hoyt, K.; Avizinis, E.; Amador, J. Evaluation of nitrogen concentration in final effluent of advanced nitrogen-removal onsite wastewater treatment systems (OWTS). Water Air Soil Pollut. **2017**, 228, 1–16.

[63] O'Driscoll, M., Bean, E., Mahoney, R.N., and Humphrey, C. 2019. Coastal tourism and its influence on wastewater nitrogen loading: A barrier island case study. Environmental Management 64: 436–455.

[64] Oakley S, Gold A, Ockzkowski A (2010) Nitrogen control through decentralized wastewater treatment: process performance and alternative management strategies. Ecol Eng 36(11):1520–1531.

Wastewater strength may have also been a factor influencing treatment efficiency of the different technologies. For each subgroup of OWTS, the system with the highest efficiency also had the highest median concentration of TDN in wastewater. The same is true for the package treatment plants and centralized sewer. While the concentration reductions observed by the OWTS were often greater than 65%, concentrations of TDN in groundwater beneath the systems were typically higher than concentrations discharged by the package plants and sewer plants. For example, median TDN concentrations in package plant effluent were under 15 mg L^{-1} for VB and CS which discharge directly to surface waters. The sewer plants both discharged median concentrations of TDN that were below 5 mg L^{-1}. However, median groundwater TDN concentrations exceeded 20 mg L^{-1} for 75% of the OWTS evaluated. Most (5 of 8) of the OWTS had NO_3^- concentrations in groundwater that exceeded the 10 mg L^{-1} standard. While most OWTS were efficient at lowering concentrations of TDN, the fate of groundwater transported NO_3^- towards surface waters is something that should be taken into consideration. Where groundwater interacts with organic-rich soils of wetlands, riparian zones, and stream beds, NO_3^- loss via denitrification may be significant. Prior studies have reported removal efficiencies of NO_3^- in groundwater that exceed 80% as groundwater moves through organic rich soils.[65] [66] However, if there is insufficient organic matter in the soil adjacent to waterways, or if the OWTS are not effective at nitrifying the wastewater, then NO_3^- or TKN [67] may discharge to surface waters, increasing watershed nitrogen exports.[68]

Some of the reduction in TDN concentrations between the drainfield trenches and water table at the OWTS sites was due to dilution and mixing with other waters (e.g., groundwater, infiltrating rain). To estimate mass removal, ratios of nutrients to chloride in wastewater and groundwater were compared at several sites. Mass removal efficiencies followed the same trend as concentration reduction efficiencies at BS, with the gravity-flow conventional OWTS performing the best (69.8%) followed by the LPP systems (26.1 to 50%). The pump to conventional-style system at JW performed the worst (5.3%) with regards to mass removal of N in the vadose zone. A groundwater well within a forested riparian area and a spring approximately 100 ft down-gradient from the OWTS at JW were also sampled during the study to assess fate and transport of nutrients. Median concentrations of TDN were 14.11 mg L^{-1} at the spring and 6.11 mg L^{-1} at the well. Concentration reductions of between 72% (spring) and 88% (well) were observed at JW as groundwater moved 100 ft away from the drainfield and through wetland soils. Mass removal of TDN within the riparian zone was between 44% (spring) and 88% (riparian well). The higher efficiency near the well was attributed to more organic matter in the soil at that location. The spring effectively flushed organic matter from the surface and was mostly sand. These data reveal that the environmental conditions between the OWTS drainfield and receiving waters also plays an important role in determining the loading of nutrients to surface waters.

[65] O'Driscoll, M.A., Humphrey Jr, C.P., Deal, N.E., Lindbo, D.L., and Zarate-Bermudez, M.A. (2014). Meteorological Influences on Nitrogen Dynamics of a Coastal Onsite Wastewater Treatment System. *Journal of Environmental Quality* 43 (6) 1873-1885. DOI: 10.2134/jeq2014.05.0227.

[66] Robertson, W.D.; Cherry, J.A.; Sudicky, E.A. Ground-water contamination from two small septic systems on sand aquifers. Groundwater **1991**, 29, 82–92.

[67] Iverson, G., O'Driscoll, M.A., Humphrey Jr, C.P**,** Manda, A.K., and Anderson-Evans, E. (2015). Wastewater Nitrogen Contributions to Coastal Plain Watersheds, NC, USA. *Water, Air & Soil Pollution.* 226 (10) 355. DOI:10.1007/sll270-015-2574-4.

[68] O'Driscoll, M., Bean, E., Mahoney, R.N., and Humphrey, C. 2019. Coastal tourism and its influence on wastewater nitrogen loading: A barrier island case study. Environmental Management 64: 436–455.

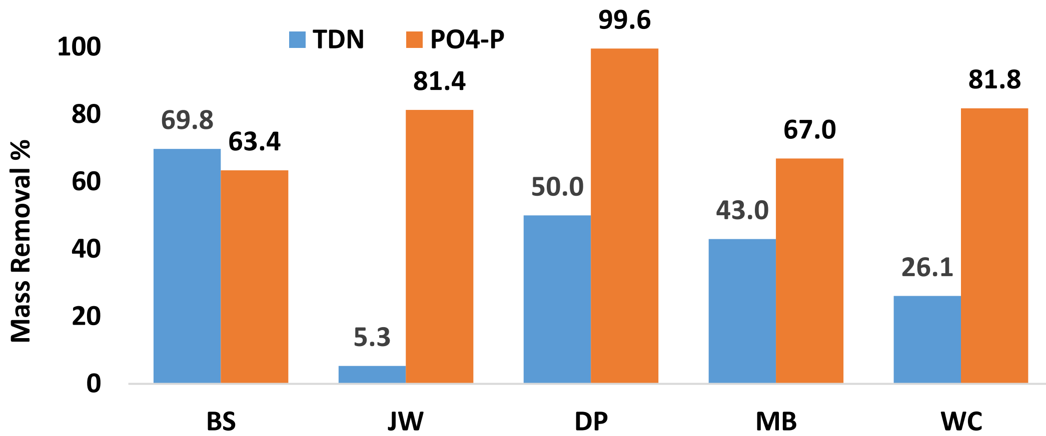

Figure 4.3. Mass removal estimates of nitrogen and phosphate based on the median differences in nutrient to chloride ratios for wastewater and groundwater at the sites with onsite wastewater systems.

4.4 Phosphorus treatment

Treatment of PO_4-P with regards to concentration reductions was greater than 79% for all OWTS except RS, where groundwater inundated the drainfield trenches (**Figure 4.4**). The centralized sewer plants reduced PO_4-P concentrations by an average of 76.9%. The package treatment plants as a group were the least efficient wastewater technologies at lowering PO_4-P concentrations. Two plants (JC and CS) had median efficiencies of less than 5%, and the overall mean efficiency for the group was a 29.6% reduction. These findings are similar to results reported by Mahoney [69] who evaluated the phosphorus treatment efficiency of 7 package plants in coastal North Carolina and found the mean efficiency was 25%. The VB package plant in the current study performed the best (84.7%) for the technological group and was the 7th most efficient of the 13 individual systems monitored. Overall, the 4 technologies that were most efficient at PO_4-P concentration reductions were all OWTS and included (BS, FB, OAK, and DP).

Unlike with TDN reduction efficiencies, there was not a clear pattern regarding OWTS subgroup differences in PO_4-P treatment. The mean efficiencies for gravity flow conventional OWTS (excluding RS) was 90.2%, while pump to conventional style OWTS (JW, OAK) were 92.7%, and low-pressure pipe systems reduced PO_4-P concentrations by an average of 87%. Thus, all technologies with sufficient mean vertical separation (> 2 ft) to groundwater were effective at PO_4-P treatment. The NB and GV sewer plants with biological nutrient removal and sand filtration processes were effective at lowering PO_4-P concentrations and loadings by 88.8% and 65%, respectively (**Figure 4.4**). The package treatment plant at CS may need to add alum or another chemical to encourage precipitation of PO_4-P minerals to increase the PO_4-P treatment efficiency prior to surface waters discharge of effluent.[70] Because effluent from the JC plant is land applied, additional treatment of PO_4-P likely occurs via adsorption in subsoil beneath the spray fields and by immobilization via plant uptake.

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[69] Mahoney R (2016) Nutrient and bacteria dynamics from package treatment plants in coastal Carteret County, North Carolina. MS Thesis, East Carolina University, Greenville, NC.

[70] Omoike, A.I., and Vanloon, G.W. 1999. Removal of phosphorus and organic matter removal by alum during wastewater treatment. Water Research 33,17, 3617-3627.

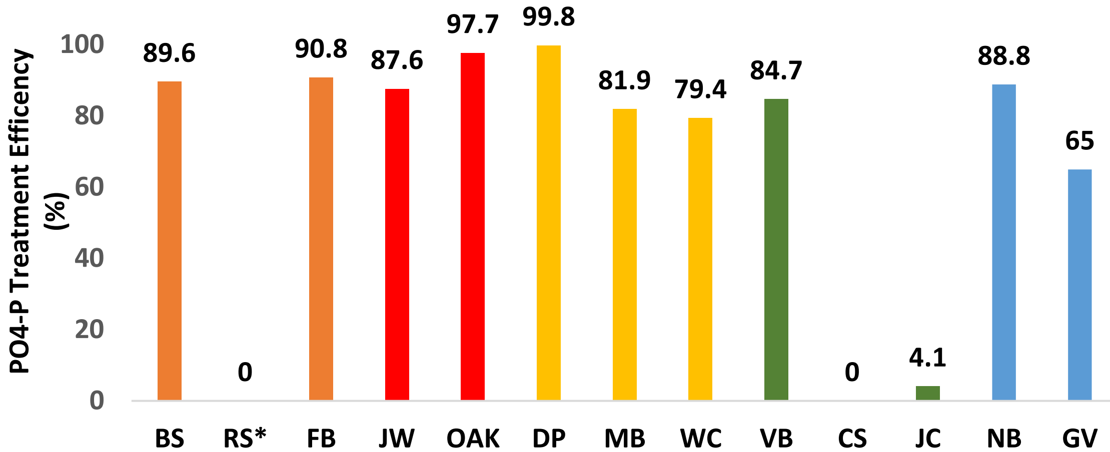

Figure 4.4. Phosphate (PO_4-P) treatment efficiency for each monitored technology based upon differences in median concentrations in wastewater/influent and groundwater/effluent. Orange indicates gravity-flow conventional systems, red are pump to conventional, yellow are low-pressure pipe, green are package plants and blue are centralized sewer sites.

Table 4.6. Concentrations of total dissolved nitrogen phosphate (PO_4-P) in wastewater sampled from the septic tanks and groundwater near the drainfield trenches of the onsite wastewater systems, and from influent and effluent at the centralized wastewater systems.

		Wastewater PO_4-P (mg L^{-1})			Groundwater PO_4-P (mg L^{-1})		
Site	**System Type**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
BS	Gravity, Conv.	18.07	14.5	22.23	1.88	0.11	3.92
RS*	Gravity, Conv.	6.48	5.96	8.45	6.48	5.96	8.45
FB	Gravity, Conv.	14.04	13.86	14.23	1.29	0.42	1.98
JWS	Pump, Conv.	4.85	0.06	9.57	0.6	0.01	4.77
OAK	Pump, Conv.	5.6	1.21	8	0.13	0.01	0.85
DP	LPP	18.62	6.53	24.68	0.03	0.01	0.06
MB	LPP	8.97	7.08	13.38	1.62	0.18	2.07
WC	LPP	2.33	0.24	9.6	0.48	0.07	1.14

		Influent PO_4-P (mg L^{-1})			Effluent PO_4-P (mg L^{-1})		
Site	**System Type**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
VB	Package Plant	3.01	0.7	17.29	0.46	0.14	1.89
CS	Package Plant	4.98	2.84	10.65	6.01	4.33	8.16

JC	Package Plant	6.05	2.32	7.87	5.8	3.37	6.2
NB	Sewer	2.32	1.6	3.23	0.26	0.04	0.93
GV	Sewer	2.94	1.47	8.8	1.03	0.14	2.15

Concentrations of PO_4-P were higher in wastewater at the OWTS sites (mean 9.87 mg L^{-1}) relative to the package plants (4.68 mg L^{-1}) and the centralized sewer sites (2.63 mg L^{-1}) (**Table 4.6**). However, these values are within the range of phosphorus concentrations in wastewater reported in reviews of literature by the US EPA[71], Lombardo[72], and Lowe et al.[73]. There was great variability among the OWTS with concentrations ranging from 2.33 mg L^{-1} at WC to 18.62 mg L^{-1} at DP. Wastewater strength may have influenced the PO_4-P treatment efficiency within OWTS subgroups. For example, the systems with the highest treatment efficiency for gravity flow conventional style OWTS (BS), pump to conventional OWTS (OAK), and low-pressure pipe OWTS (DP) all had the highest median concentrations of PO_4-P in wastewater for their subgroup. The same pattern was not observed for package plants where VB had the highest efficiency but lowest median concentration of PO_4-P in wastewater, or sewer plants where NB had the highest treatment efficiency but lowest median PO_4-P concentration in wastewater. Overall, OWTS that met the required vertical separation distance to groundwater were the most efficient technologies for reducing PO_4-P concentrations.

Based on the differences in PO_4-P to chloride ratios for wastewater and groundwater near the OWTS, the estimated average mass removal of PO_4-P by the OWTS was 78.6%. Thus, OWTS were also more efficient on average than package treatment plants 44.4% and centralized sewer systems 76.9% at PO_4-P mass removal. Adsorption and/or mineral precipitation processes likely contributed to the treatment efficiencies of the OWTS. The mean pH (range 3.7 to 7.1) and oxidation reduction potential (range -47 to 80) of groundwater beneath the trenches would allow for precipitation of phosphate minerals if iron and aluminum were available in the soil solution.[74]

Phosphorus concentration reductions of greater than 75% were reported for three OWTS in coastal Virginia [75] and four OWTS in coastal North Carolina [76] indicating that in some settings, OWTS are very effective at phosphorus treatment. However, it has also been shown that in sandy soils when the water table is within 2 ft of the drainfield trenches, groundwater near the OWTS and more than 50 ft down-

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[71] United States Environmental Protection Agency (2002) Onsite wastewater treatment systems manual. EPA/625/R-00/008.Washington, DC: Office of Water, Office of Research and Development.

[72] Lombardo, P. Phosphorus Geochemistry in Septic Tanks, Soil Absorption Systems, and Groundwater; Lombardo Associates, Inc.: Newton, MA, USA, 2006.

[73] Lowe KS, Tucholke MB, Tomaras JMB, Conn K, Hoppe C, Drewes JE, McCray JE, Munakata-Marr J (2009) Influent constituent characteristics of the modern waste stream from single sources. Water
Environ Res Found. Technical report.

[74] Lombardo, P. Phosphorus Geochemistry in Septic Tanks, Soil Absorption Systems, and Groundwater; Lombardo Associates, Inc.: Newton, MA, USA, 2006.

[75] Reay, W.G. Septic Tank Impacts on Groundwater Quality and Nearshore Sediment Nutrient Flux. *Groundwater* 2004, *42*, 1079–1089. https://doi.org/10.1111/j.1745-6584.2004.tb02645.x.

[76] Humphrey, C., Anderson-Evans, E., O'Driscoll, M., Manda, A., and Iverson, G. (2015). Comparison of Phosphorus Concentrations in Coastal Plain Watersheds Served by Onsite Wastewater Treatment Systems and a Municipal Sewer Treatment System. *Water Air & Soil Pollution. DOI 10.1007/s11270-014-2259-4.*

gradient may have elevated concentrations of phosphorus.[77] [78] While most of the OWTS evaluated in this study were efficient, the median concentration of PO_4 in groundwater beneath 4 of 8 systems (50%) exceeded 1.0 mg L^{-1} (**Table 4.6**). Effluent discharged from the GV sewer plant, and the CS and JC package plants also exceeded 1 mg L^{-1}. These concentrations are more than an order of magnitude higher than concentrations that may stimulate algal blooms in some surface waters.[79] Because the OWTS discharges effluent to subsoil and the JC package plant effluent is land-applied, any phosphorus that enters groundwater at those sites may undergo further treatment (e.g., immobilization, sorption) as groundwater moves towards surface waters. That is not true of the centralized sewer systems and VB and CS package plants that discharged directly to surface waters.

4.5 Bacteria treatment

Except for the OWTS at RS, all wastewater treatment systems evaluated during this project were effective at reducing the concentration of *E. coli* prior to effluent reaching water resources. The median concentration of *E. coli* in groundwater near the OWTS was under 4 MPN 100 mL^{-1} for every system aside from RS. The package treatment plants and centralized sewer systems also had median concentrations of *E. coli* in their effluent under 4 MPN 100 mL^{-1}. Wastewater strength was highly variable between OWTS, package treatment plants and the centralized sewer systems. There were 2 orders of magnitude difference in the median concentrations of *E. coli* in wastewater between some of the sites; however, the range in concentrations observed in this study have also been reported in prior literature reviews (Lowe et al. 2009).[80] Because groundwater at RS was within the drainfield trenches during each sampling event, septic tank effluent with a median *E. coli* concentration of 185,000 MPN 100 mL^{-1} was being discharged directly to the water table without soil filtration. The other OWTS each had mean separation distances that exceeded 2 ft, and thus were in compliance with local regulations and were efficient (> 99.99%) at reducing *E. coli* concentrations.

Prior studies in coastal North Carolina[81] [82] [83] have shown that vertical separation to groundwater is one of the most important factors regarding treatment of bacteria. Concentrations of indicator bacteria are

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[77] Corbett, D.R.; Dillon, K.; Burnett,W.; Schaefer, G. The Spatial Variability of Nitrogen and Phosphorus Concentration in a Sand Aquifer Influenced by Onsite Sewage Treatment and Disposal Systems: A Case Study on St. George Island, Florida. Environ. Pollut. **2002**, 117, 337–345.

[78] Humphrey, C.P.; O'Driscoll, M.A.; Deal, N.; Lindbo, D. Fate and Transport of Phosphate from an On-Site Wastewater System in Beaufort County, North Carolina. J. Environ. Health **2014**, 76, 28–33.

[79] Lombardo, P. Phosphorus Geochemistry in Septic Tanks, Soil Absorption Systems, and Groundwater; Lombardo Associates, Inc.: Newton, MA, USA, 2006.

[80] Lusk, M.G.; Toor, G.S.; Yang, Y.-Y.; Mechtensimer, S.; De, M.; Obreza, T.A. 2017. A review of the fate and transport of nitrogen, phosphorus, pathogens, and trace organic chemicals in septic systems. Crit. Rev. Environ. Sci. Technol. 47: 455–541.

[81] Humphrey, C. P., O'Driscoll, M. A., & Zarate, M. A. (2011). Evaluation of On-site Wastewater System *E. coli* Contributions to Shallow Groundwater in Coastal North Carolina. *Water Science and Technology 63 (4), 789-795*.

[82] Conn, K. E., Habteselassie,M. Y., Blackwood, A. D., & Noble, R. T. (2011). Microbial water quality before and after the repair of a failing onsite wastewater treatment system adjacent to coastal waters. Journal of Applied Microbiology, 112, 214–224.

[83] Humphrey, C.P., Finley, A.J., O'Driscoll, M.A., Manda, A., and Iverson, G. (2015) Groundwater and Stream *E. coli* Concentrations in Coastal Plain Watersheds Served by Onsite Wastewater and a Municipal Sewer Treatment System. *Water Science and Technology* 72(10) 1851-1890. doi:10.2166/wst.2015.411.

typically reduced by more than 90% when there is 1 ft of separation distance to the water table[84] [85] [86], however, elevated concentrations of bacteria may still be observed in that scenario (1 ft separation), suggesting a thicker vadose zone may be required. Significant differences in *E. coli* concentrations in groundwater beneath OWTS in coastal North Carolina were reported when comparing OWTS with more than 2 ft (0.6 m) of separation to OWTS with under 1.5 ft (0.45 cm) of separation.[87] A column study by Stall et al. [88] showed that the concentrations of *E. coli* in effluent leached through 2 ft (0.6 m) of soil were significantly lower relative to concentrations passing through 1 ft (0.3 m) and 1.5 ft (0.45 m) of soil. Research has shown that groundwater influenced by OWTS with insufficient separation distances (< 1 ft or < 0.3 m) may deliver bacteria to adjacent surface waters and contribute to watershed exports of bacteria.[89]

Groundwater quality and surface water quality are often linked in coastal areas.[90] [91] Malfunctioning OWTS have been suggested as a major contributing source of bacterial pollution to coastal waters in North Carolina [92] [93] and Florida. [94] Elevation of OWTS drainfield trenches to increase the separation distance to the water table has been shown to reduce the concentration of bacteria in groundwater and improve the treatment efficiency of the OWTS.[95] While all technologies aside from RS were efficient (>99%) at reducing *E. coli* concentrations, both centralized sewer systems and the VB package plant, which discharge effluent directly into streams, had frequencies of *E. coli* detections that were 50% or greater. The sewer plants at NB and GV typically discharge effluent at rates of 5 million gallons per day (18.9 million liters per day) and 10 million gallons per day (37.8 million liters per day), respectively, and the VB package plant discharges 0.25 million gallons per day (0.95 million liters per day). Therefore, while these systems are efficient, they may still be significant sources of *E. coli* loading to surface waters. The OWTS

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84 Karathanasis, A. D.,Mueller, T. G., Boone, B.,&Thompson, Y. L. (2006). Effect of soil depth and texture on fecal bacteria removal from septic effluents. Journal of Water and Health, 04(3), 395–404.

85 Humphrey, C. P., O'Driscoll, M. A., & Zarate, M. A. (2011). Evaluation of On-site Wastewater System *E. coli* Contributions to Shallow Groundwater in Coastal North Carolina. *Water Science and Technology 63 (4), 789-795*.

86 Stall, C., Amoozegar, A., Graves, A., & Rashash, D. (2014). Transport of E. coli in a sandy soil as impacted by depth to water table. Journal of Environmental Health, 76(6), 92–100.

87 Humphrey, C. P., O'Driscoll, M. A., & Zarate, M. A. (2011). Evaluation of On-site Wastewater System *E. coli* Contributions to Shallow Groundwater in Coastal North Carolina. *Water Science and Technology 63 (4), 789-795*.

88 Stall, C., Amoozegar, A., Graves, A., & Rashash, D. (2014). Transport of E. coli in a sandy soil as impacted by depth to water table. Journal of Environmental Health, 76(6), 92–100.

89 Humphrey, C.P., Finley, A.J., O'Driscoll, M.A., Manda, A., and Iverson, G. (2015)
Groundwater and Stream *E. coli* Concentrations in Coastal Plain Watersheds Served by Onsite Wastewater and a Municipal Sewer Treatment System. *Water Science and Technology* 72(10) 1851-1890. doi:10.2166/wst.2015.411.

90 Humphrey, C.P., Finley, A.J., O'Driscoll, M.A., Manda, A., and Iverson, G. (2015) Groundwater and Stream *E. coli* Concentrations in Coastal Plain Watersheds Served by Onsite Wastewater and a Municipal Sewer Treatment System. *Water Science and Technology* 72(10) 1851-1890. doi:10.2166/wst.2015.411.

91 Iverson, G., O'Driscoll, M.A., Humphrey Jr, C.P**,** Manda, A.K., and Anderson-Evans, E. (2015). Wastewater Nitrogen Contributions to Coastal Plain Watersheds, NC, USA. *Water, Air & Soil Pollution.* 226 (10) 355. DOI:10.1007/sll270-015-2574-4.

92 Cahoon, L. B., Hales, J. C., Carey, E. S., Loucaides, S., Rowland, K. R., & Toothman, B. R. (2016). Multiple modes of water quality impairment by fecal contamination in a rapidly developing coastal area: Southwest Brunswick County, North Carolina. Environmental Monitoring and Assessment, 188, 89. https://doi.org/10.1007/s10661-015-5081-6.

93 Mallin, M. A., McIver, M. R., & Matthew, R. (2012). Pollutant impacts to Cape Hatteras National Seashore from urban runoff and septic leachate. Marine Pollution Bulletin, 64(7), 1356–1366.

94 Meeroff, D. E., Bloetscher, F., Bocca, T., & Morin, F. (2008). Evaluation of water quality impacts of on-site treatment and disposal systems on urban coastal waters.Water, Air, and Soil Pollution, 192, 11–24.

95 Conn, K. E., Habteselassie,M. Y., Blackwood, A. D., & Noble, R. T. (2011). Microbial water quality before and after the repair of a failing onsite wastewater treatment system adjacent to coastal waters. Journal of Applied Microbiology, 112, 214–224.

that met the state required vertical separation to groundwater (all except RS) had detection frequencies ranging from 0% at FB to 50% at BS, with most between 30% and 40% (Table 4.7).

Table 4.7. Concentrations of *E. coli* in wastewater sampled from the septic tanks and groundwater near the drainfield trenches of the onsite wastewater systems, and from influent and effluent at the centralized wastewater systems.

		Wastewater *E. coli* (MPN 100 mL^{-1})			**Groundwater *E. coli* (MPN 100 mL^{-1})**			
Location	**System Type**	**Median**	**Min**	**Max**	**Median/Mean**	**Min**	**Max**	**Freq > 1**
BS	Gravity, Conv.	291500	1999	8664500	2/14	0	70	0.5
RS*	Gravity, Conv.	185000	75000	190500				1
FB	Gravity, Conv.	34250	22800	45700	3/3	0	6	0
JWS	Pump, Conv.	391500	5000	4839200	2/2	0	7	0.4
OAK	Pump, Conv.	280650	15750	3635000	1/6	0	30	0.37
DP	LPP	91250	2419	1790000	<1/6	0	36	0.3
MB	LPP	280500	63000	12098000	1/3	0	16	0.3
WC	LPP	3365000	21800	7258800	1/9	0	72	0.4

		Influent *E. coli* (MPN 100 mL^{-1})			**Effluent *E. coli* (MPN 100 mL^{-1})**			
Location	**System Type**	**Median**	**Min**	**Max**	**Median/Mean**	**Min**	**Max**	**Freq > 1**
VB	Package Plant	7765500	4848000	17329000	2/9	0	10	0.7
CS	Package Plant	2029000	298000	8664000	<1/3	0	20	0.25
JC	Package Plant	1385750	1149000	13340000	<1/307	0	2419	0.25
NB	Sewer	4839200	572500	10112000	2/12	0	91	0.56
GV	Sewer	4839200	980000	12098000	3/4	0	16	0.5

5. Perspectives from onsite wastewater managers

By Jane Harrison, Ph.D., and Lauren Vorhees, North Carolina Sea Grant, North Carolina State University

Despite the vulnerabilities of OWTS to increased precipitation and sea level rise, there is little known about how onsite wastewater managers are responding to current and future climate risks. We conducted interviews with wastewater operators and installers and health regulators to understand the functioning, management, and regulation of OWTS in the current climate; challenges with rising sea levels and increases in extreme weather events; and what adaptation strategies can be implemented to mitigate negative impacts. The full results of the interviews are available;[96] [97] in this report, we summarize the key takeaways.

In 2020, a total of 28 OWTS managers in coastal Carolina counties (**Figure 5.1**) voluntarily participated in a phone interview composed of open-ended questions related to their professional experience with OWTS in their locale. The group consisted of experts from the private and public sectors: 20 onsite wastewater operators/installers and 8 county and state health regulators. Wastewater operators/installers are private contractors that install, operate and repair onsite systems. Health regulators are charged with permitting OWTS and determining which types of systems and properties are appropriate for onsite wastewater treatment.

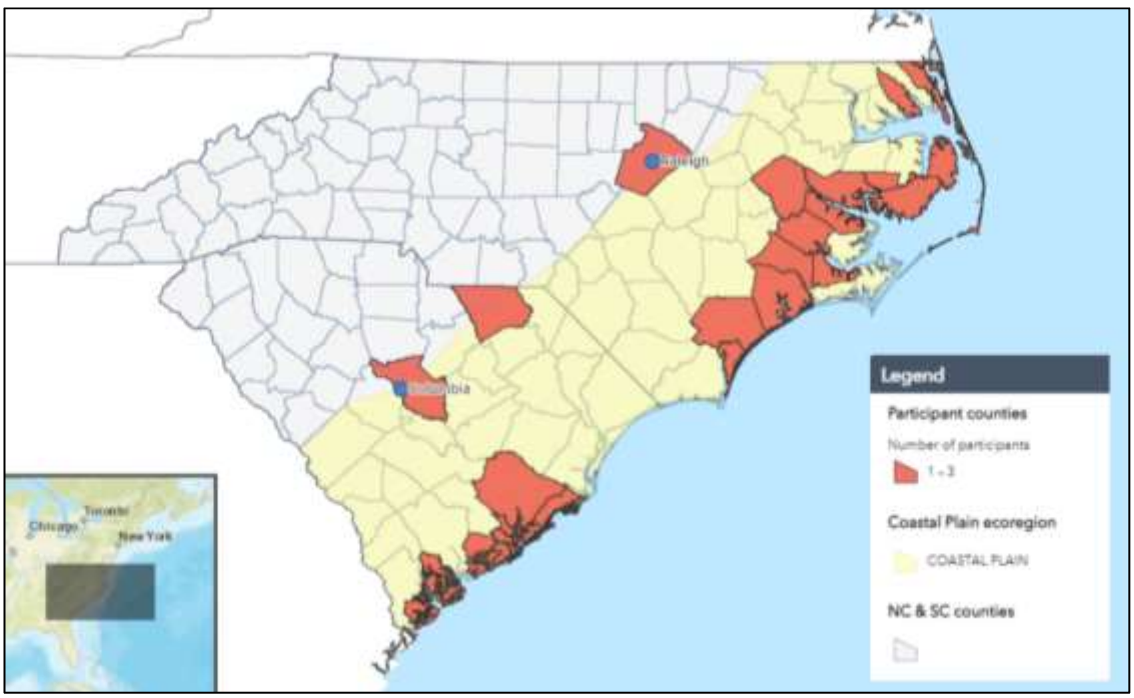

Figure 5.1. The Carolina coastal counties where the OWTS experts were located when interviewed for this study.

Our findings suggest the following takeaways about OWTS and climate resilience: a. weather and climate are important but unaccounted considerations in site approval and system selection; b. current regulations are inadequate to deal with future climate risks; c. adaptation is happening regardless of

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96 Vorhees, L., J. Harrison, M. O'Driscoll, C. Humphrey Jr., J. Bowden. 2022. Climate Change and Onsite Wastewater Treatment in the Coastal Carolinas: Perspectives from Wastewater Managers. *Weather, Climate & Society.* In Press.

97 Vorhees, L. and J. Harrison. 2021. Climate Change and Onsite Wastewater Treatment Systems in the Coastal Carolinas: Perspectives from Wastewater Managers. North Carolina Sea Grant, UNC-SG-21-06. https://ncseagrant.ncsu.edu/wp-content/uploads/2021/09/Perspectives-from-OWTS-Managers-REPORT_Aug-24-2021.pdf.

regulations; and d. system owners would benefit from additional communications about system maintenance. The takeaways are depicted in **Figure 5.2**.

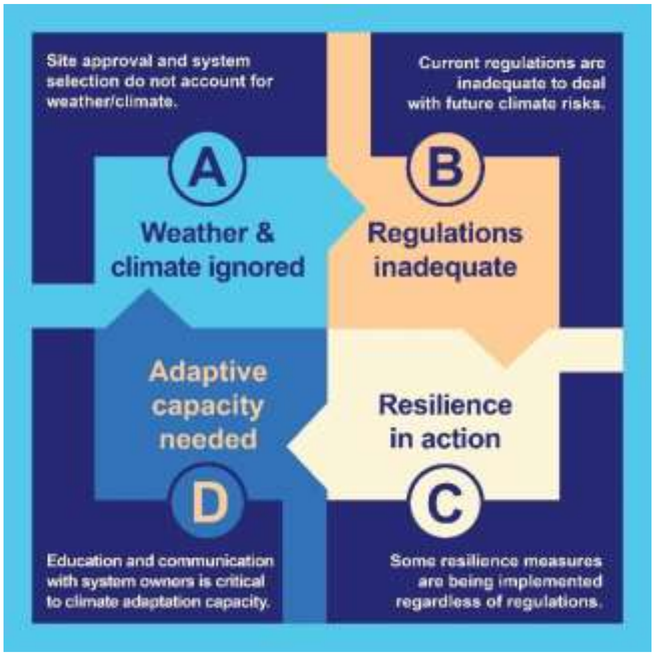

Figure 5.2. Four key takeaways from wastewater managers about onsite wastewater treatment and climate resilience. Source: Illustration by Melissa D. Smith[98]

5.1 Weather and climate not considered in site approval and system selection

Despite the upward trend of storm frequency and severity in the coastal Carolinas, along with sea level rise observed in low-lying areas of the region, and its negative impacts on OWTS,[99] [100] [101] weather and climate do not directly impact site approval or system selection. What type of system will be installed is determined on a case-by-case basis and decided based on the conditions on the day of evaluation, including vertical separation distance, soil morphology, available space, and distance to surrounding surface waters. No buffer for rising groundwater conditions is required.

And yet disruptive weather events like heavy rainfall or king tides negatively impact OWTS wherever site variables are undesirable. Site conditions *combined with* frequency and duration of saturation events are valuable information to determine system functionality as climate change intensifies. Interviewees acknowledged that it would be beneficial for long-term functionality to include some aspects of weather and climate when evaluating sites for installation.

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[98] Vorhees, L., J. Harrison, M. O'Driscoll, C. Humphrey Jr., J. Bowden, 2022: Climate change and onsite wastewater treatment systems in the coastal Carolinas: Perspectives from wastewater managers. *Weather, Climate and Society*. In Press.

[99] Paerl, H.W., N. S. Hall, A. G. Hounshell, R. A. Luettich, K. L. Rossignol, C. L. Osburn, and J. Bales, 2019: Recent increase in catastrophic tropical cyclone flooding in coastal North Carolina, USA: Long-term observations suggest a regime shift. Sci. Rep., 9, 1–9, https://doi.org/10.1038/s41598-019-46928-9.

[100] Amador, J., G. Loomis, K. Kalen, 2014: Soil-based onsite wastewater treatment and the challenges of climate change. Proceedings, innovation in soil-based onsite wastewater treatment, Albuquerque, NM. Retrieved from https://www.soils.org/files/meetings/specialized/full-conference-proceedings.pdf.

[101] Manda, A. K., M. S. Sisco, D. J. Mallinson, and M. T. Griffin, 2014: Relative role and extent of marine and groundwater inundation on a dune-dominated barrier island under sea-level rise scenarios. Hydrological Processes, 29 (8), 1894-1904.

Site conditions are affected by the season, weather patterns, and time of day within the current climate regime. For example, future climate shifts will alter groundwater table elevation at inland sites and the mean high water mark on ocean-side lots, which can affect the setbacks measured at the site evaluation. More than half (63%) of health regulators interviewed reported that rising water table conditions is one of the biggest challenges facing OWTS in coastal communities, in addition to limited space available, saltwater intrusion, and insufficient OWTS regulations (**Figure 5.3**). Ultimately, measurements taken at the initial site evaluation are insufficient for accounting for weather and climate impacts on the systems into the future. **Figure 5.4** depicts under what conditions a septic system is likely to malfunction.

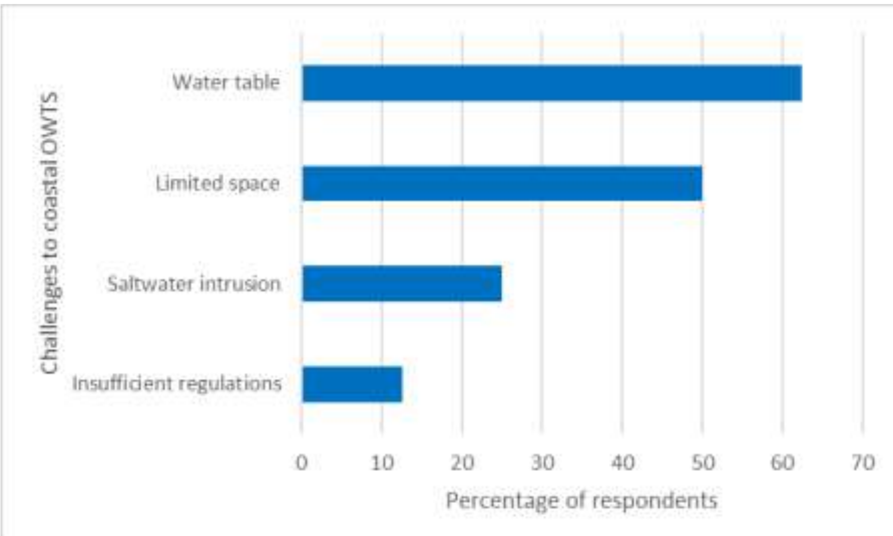

Figure 5.3. The biggest challenges reported by health regulators interviewed.

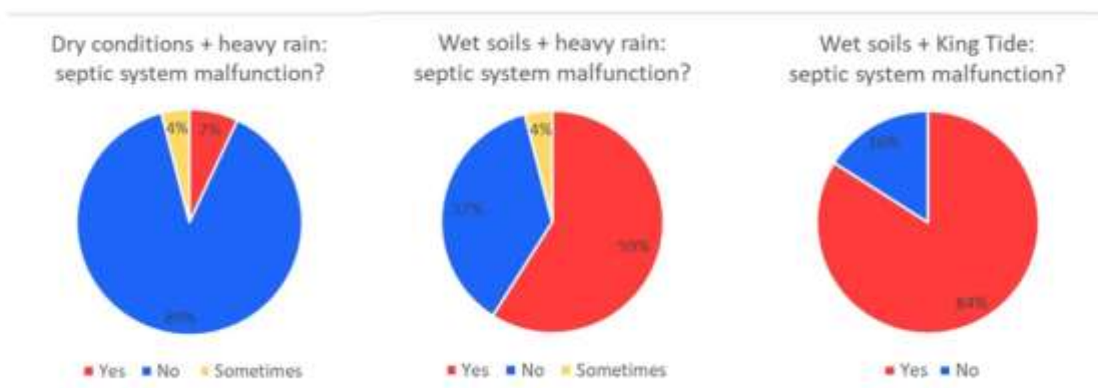

Figure 5.4. Septic system malfunction in three hypothetical weather scenarios.

5.2 Regulations needed to adapt OWTS to a changing climate

Despite ample evidence that coastal Carolina's climate will be wetter, policies and practices that encourage resilience are slow to follow due to the many barriers and obstacles affecting decision makers, such as lack of funding or systemic collaboration between state and local agencies.[102] Previous studies of centralized wastewater managers revealed that the changes they are making to adapt to storms similar to

[102] Tryhorn, L, 2010: Improving policy for stormwater management: implications for climate change adaptation. Weather, Climate, and Society, 2 (2), 113-126. https://doi.org/10.1175/2009WCAS1015.1.

past storms was voluntarily initiated, whereas adaptation to future climate change impacts requires regulatory action and requirement changes.[103] Our findings suggest a similar conclusion for onsite wastewater management; adaptation to changes in weather and climate are limited by regulations. A health regulator interviewed said there are new onsite wastewater treatment technologies available and that some of the advanced pretreatment systems are proving to be more robust and sustainable. However, these more resilient systems must be included in regulations for them to become widespread.

Our findings suggest that municipalities and health departments lack sustainable programs to assist owners with proper system operation. An ongoing program that tracks system inspections and maintenance could ensure systems remain well-maintained and compliant with regulations. Inspections of conventional septic systems are not required, which means there are limited data on how systems are performing over time as well as before and after disruptive weather events.

5.3 Resilience actions being taken by system managers

Even though adjustments for weather and climate are not required when installing a system and regulations may limit the advancement of OWTS technological innovations for climate adaptation, over half (60%) of operators/installers interviewed are taking it upon themselves to improve OWTS functionality in response to recent changes in weather and soil conditions. For example, some system installers are installing tanks and drainlines higher in the ground to allow more vertical separation when it is permissible within the parameters of the permit. Others are being more conservative during installation by installing additional drainlines or using a larger septic tank. A S.C. state health regulator explained, “we do have a 12 in vertical setback [separation distance] to meet…[but] it’s common for our inspectors to add a little bit of a buffer in there for [extreme weather] and to allow for human error when digging the trenches.” **Figure 5.5** depicts recommendations for advanced treatment options by the experts interviewed.

[103] Kirchhoff, C. J. and P. L. Watson, 2019: Are Wastewater Systems Adapting to Climate Change? Journal of the American Water Resources Association, 55 (4), 869-880, https://doi.org/10.1111/1752-1688.12748.

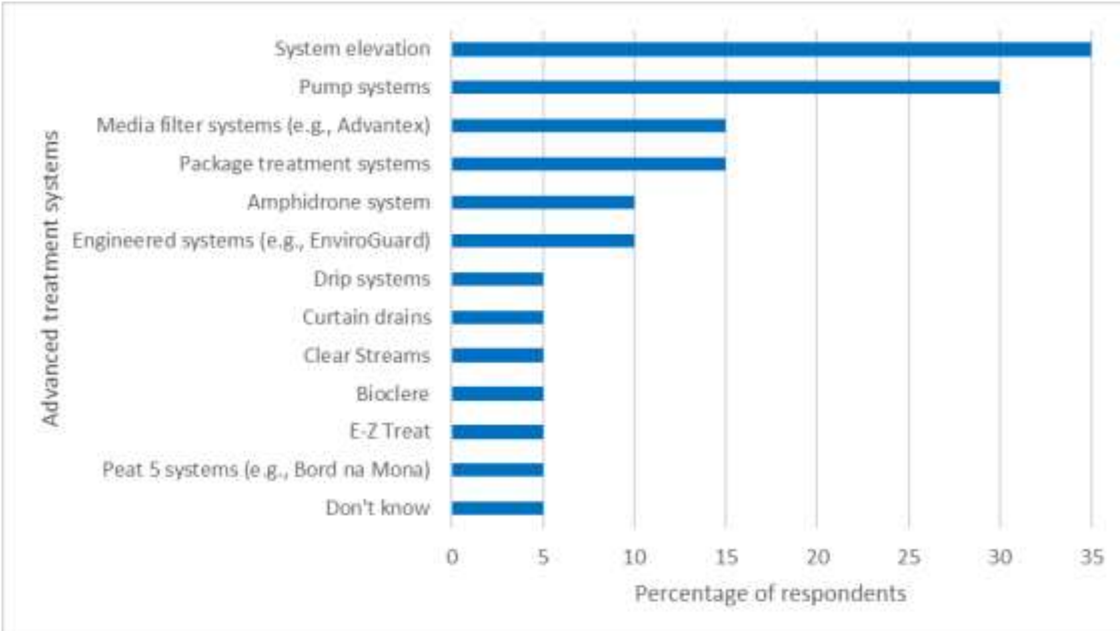

Figure 5.5. Recommendations for advanced treatment system options for handling extreme weather.

Resilience actions are generally being taken by installers in reaction to past disruptive weather events in an attempt to maintain capacity of the systems in similar events, not necessarily for storms that may be experienced in the future as the climate continues to shift. Education about proactive measures to increase the resilience of systems should be a key component of OWTS adaptation. University extension and outreach programs are well positioned to educate installers, operators, health officials, and the general public of the increasing risks to septic systems from climate impacts and system options. Adaptation measures relevant to a given locality would be more likely to be implemented if continuing education on these topics was available.

Resiliency planning for wastewater infrastructure is occurring in some communities but they are the exception rather than the rule. The Town of Nags Head, N.C. is a leader with its Septic Health Initiative that provides free septic system inspections, water utility bill credits for septic system pump outs, low-interest loans for septic system repairs or replacement, and water quality testing.[104] New York City developed a climate risk management framework for strategic and capital planning of their water systems.[105] Miami-Dade County and St. Augustine in Florida have both completed comprehensive vulnerability assessments of the impacts of climate change on the OWTS in their locality,[106] and Florida has instituted a state-wide water management inventory project that provides an interactive online map

[104] Miller, H., 2022: Town of Nags Head North Carolina Decentralized Wastewater Management Plan. *Tetra Tech Engineering, PC.* Presented by Tetra Tech Engineering. Presented to Town of Nags Head.

[105] Rosenzweig, C., D. C. Major, K. Demong, C. Stanton, R. Horton, and M. Stults, 2007: Managing climate change risks in New York City's water system: assessment and adaptation planning. *Mitig Adapt Strat Glob Change*, **12**: 1391-1409.

[106] Miami-Dade County Department of Regulatory & Economic Resources, Miami-Dade County Water and Sewer Department, and Florida Department of Health in Miami-Dade County, 2018: Septic systems vulnerable to sea level rise. Final Rep. in Support of Resolution No. R-911-16. Miami: Miami-Dade County Dept. of Regulatory & Economic Resources, Miami-Dade County Water and Sewer Dept., and Florida Dept. of Health in Miami-Dade County.

of domestic wastewater disposal types and locations that is available for public use.[107] The Georgia Department of Public Health has also instituted a program to provide a web-based method for tracking private well and sewage treatment installation data.[108] These communities are on the frontlines of OWTS adaptation to climate change in the US, providing insight into the types of actions coastal communities can take in order to implement climate resiliency planning for wastewater infrastructure.

5.4 Adaptive capacity needed for communities

What can communities do for their residents? Two important areas of interest are communication and education. Prior research shows that effective communication with the public and education with wastewater managers are essential to implementing and strengthening climate adaptation measures in the infrastructure sector.[109] [110] [111]

Interviews with septic experts revealed that communication between OWTS regulatory authorities and property owners is limited and inconsistent, contributing to system malfunction. Interviewees explained that the local health department is responsible for communication, and as a result, the information provided to homeowners varies by location. Owners are provided information on their system at the time of installation, but after that, it is up to the homeowner to seek the information out (e.g. by calling the state or local health department or searching for answers online). Consistent communication with property owners, particularly in regards to information on system maintenance and causes of malfunction, could greatly improve owners' preparedness for and response to weather events.

Flood risk communication is also lacking with system owners. Some health regulators reported that local health departments do not inform owners of flooding risk of their system. Others explained there are public service announcements sent out before or after an extreme precipitation event but to broad zones of potential flooding areas and not directly to owners of septic systems. According to a N.C. state health regulator, informing homeowners of flooding risk "would be very useful because it would allow homeowners to know what to do. Online resources and the materials we have about what to do before, during, and after a flooding event would need to be provided to homeowners."

There was consensus among participants that education or training opportunities that relate specifically to extreme weather, rising sea levels, and rising groundwater levels are not available to operators/installers or regulators. Operators and installers who work directly with onsite systems may be an untapped resource for communication with OWTS owners. Through education of operators, installers, and regulators of the increasing challenges for onsite systems from disruptive weather events and options for adaptation measures, communication with owners would improve. This could potentially

[107] Florida Health, 2021: Florida Water Management Inventory Project. *Florida Department of Health*. Retrieved from https://www.floridahealth.gov/environmental-health/drinking-water/flwmi/index.html.

[108] Southern Georgia Regional Commission, 2020: Welstrom: Well and Septic Tank Referencing and Online Mapping. Southern Georgia Regional Commission. Retrieved from: https://www.welstrom.com/help.html.

[109] Jiricka-Purrer, A., M. Leitner, H. Formayer, T. F. Wachter, and A. Prutsch, 2018: Mainstreaming Climate Change Adaptation in Infrastructure Planning – Lessons Learned from Knowledge Transfer and Communication. In: Leal Filho W., Lackner B., McGhie H. (eds) Addressing the Challenges in Communicating Climate Change Across Various Audiences. Climate Change Management. Springer, Cham, https://doi-org.prox.lib.ncsu.edu/10.1007/978-3-319-98294-6_24.

[110] Rudberg, P. M., O. Wallgren, and A. G. Swartling. 2012. Beyond Generic Adaptive Capacity: Exploring the Adaptation Space of the Water Supply and Wastewater Sector of the Stockholm Region, Sweden. *Climatic Change* **114**: 707–21.

[111] USGCRP (U.S. Global Change Research Program), 2012: The national global change research plan 2012–2021: a strategic plan for the U.S. Global Change Research Program. U.S. Global Change Research Program, National Coordination Office, Washington, DC.

ensure widespread awareness and consistent strategies being implemented in both states. Researchers and university extension professionals are well suited for distributing such outreach materials and educating OWTS managers on climate adaptation options.[112]

[112] Linder, J. and V. Campbell-Arvai, 2021: Uncertainty in the "New Normal": Understanding the Role of Climate Change Belief and Risk Perceptions in Michigan Tree Fruit Growers' Adaptation Behaviors. Weather, Climate, and Society, 13 (3), 409-422, https://doi.org/10.1175/WCAS-D-20-0058.1.

6. Legal and policy analysis for two coastal communities

By Katie Hill, J.D., Carl Vinson Institute of Government, University of Georgia

For this portion of the project, we conducted a two-state analysis of the legal regimes governing the use of septic systems, and used these analyses to define the landscape for septic system management possibilities in two coastal communities: Nags Head, N.C., and Folly Beach, S.C. We conducted research and engagement activities to accomplish the following:

- Assess the extent of local authority to regulate the use of septic systems in North Carolina and South Carolina (i.e., preemption analysis)
- Identify regulatory barriers or other challenges for policies identified as desirable by Nags Head, N.C., and Folly Beach, S.C.
- Determine practical policy approaches for Nags Head and Folly Beach to adapt the use of septic systems to climate change

We describe each of these activities below.

6.1 Local authority to regulate septic systems

Adapting the use of septic systems to climate change in coastal areas is challenging for policy makers. These systems are regulated under state law,[113] and no states have developed regulatory frameworks that specifically address climate change impacts on septic systems.[114] Coastal local governments are aware of the threats sea level rise, increased precipitation, and flooding events pose to septic systems, but it is unclear whether or not they have the authority to adopt regulatory policies addressing these impacts. Most state septic laws do not clearly state whether the law preempts (prohibits) or allows local regulation. Because state laws are not explicit, localities considering septic adaptation regulations must contend with the fact that they risk being struck down by the courts.

We conducted a legal analysis on the likelihood of preemption of local regulation of septic systems in North Carolina and South Carolina. By "local regulation of septic systems," we mean local ordinances adopted by counties and municipalities that directly impact the siting, design, installation, or use of septic systems. This would include local septic inspection or maintenance rules, rules requiring specific types of systems, and rules specifying where systems must be sited on a particular parcel. It does not include ordinances or programs that indirectly impact the use of septic systems, such as land use controls that would require large lot sizes regardless of the type of wastewater system used or setbacks or buffers required for other purposes that indirectly impact where systems can be installed.

An analysis of local authority consists of first assessing whether localities would have authority to regulate in the absence of a state law on the subject area. Here, both states have given counties and municipalities sufficient authority that, in the absence of preemptive state laws on septic systems, local governments would be authorized to adopt ordinances directly regulating the use of septic systems.

After this preliminary authority question, the next area for analysis is whether any state law preempts local action on the subject area. Where state law exists on the subject area but there is no express preemption (i.e., the legislature did not explicitly state in the law that local governments are prohibited from regulating

[113] The Clean Water Act does not regulate the use of septic systems.

[114] Virginia's legislature did adopt legislation in 2021 creating a working group to make recommendations to the state on how to incorporate climate change considerations into wastewater regulatory and funding programs.

in that area), the analysis next attempts to determine the legislature's intent on the matter to discern whether preemption was implied. When doing such an analysis, courts will consider such factors as the scope of the state's legislative framework. A preemption analysis could find preemption through examination of the scope of the entire statutory framework, or through the effect of specific provisions within the statute.

6.2 North Carolina preemption analysis

There is a provision in the North Carolina statute concerning septic systems that could be express preemption of municipal septic regulations.[115] The wording of that provision is somewhat awkward, however, so we also evaluated whether a court could find implied preemption of local septic regulations.

A court could negate local government attempts at direct septic regulation by finding implicit preemption through the state septic law's general scheme and specific provisions. North Carolina's septic statute is thorough and comprehensive and goes into great detail as to the scope of the program the legislature intended N.C. Department of Health and Human Services to develop.[116] It also provides a mechanism for local boards of health to adopt more stringent regulations based on local conditions.[117] This could be seen as evidence of legislative intent to single out boards of health as the sole authorities concerning septic system use, excluding municipal or county action on the subject. It seems likely that a court could find direct regulation of septic system use by Nags Head implicitly preempted by state law.

6.3 South Carolina preemption analysis

A provision of South Carolina law gives cities and towns the authority to "make regulations generally with respect to the discharge of sewage and the use of privies, septic tanks and any other type of sewage facilities."[118] On its own, that language appears to give municipalities broad authority to regulate septic systems. Taken in context, however, that authority may be couched by the purpose of that statute, which is to "facilitate the construction and operation of sewer systems by municipalities."[119]

South Carolina's somewhat haphazard statutory scheme for septic system regulation seems to make a finding of implied preemption of local ordinances on the subject unlikely. Regulation of septic systems in South Carolina occurs pursuant to several statutory schemes – one concerning the approval of septic systems at homesites,[120] another granting the state's Department of Health and Environmental Control (DHEC) authority to promulgate regulations,[121] and another granting municipalities powers to facilitate the construction and operation of centralized sewer systems.[122] The fact that the legislature failed to adopt a single comprehensive statute enumerating all of the areas in which DHEC must regulate septic systems, and its focus on the "abate[ment of] obnoxious and offensive odors caused or produced by septic

[115] The provision reads "Notwithstanding any other provision of law, a municipality shall not prohibit or regulate by ordinance or enforce an existing ordinance regulating the use of off-site wastewater systems or other systems approved by the Department under rules adopted by the Commission when the proposed system meets the specific conditions of the approval." N.C. GEN. STAT. § 130A-335(c2) (2022).

[116] N.C. GEN. STAT. § 130A-333 to 345 (2022).

[117] N.C. GEN. STAT. §130A-335(C) (2022).

[118] S.C. CODE ANN. § 5-31-2010 (2020).

[119] S.C. CODE ANN. § 5-31-2010 (2020).

[120] S.C. CODE ANN. § Title 44, Ch. 55, Art. 9 (2022).

[121] S.C. CODE ANN. § 44-1-140 (2022).

[122] S.C. CODE ANN. § 5-31-2010 (2022).

tank[s]"[123] as opposed to more general public and environmental health concerns could indicate that the legislature did not intend to prohibit local involvement in septic regulation.

The language of another statute concerning local government land development regulations also gives support to there being at least some local authority to regulate septic systems. The statute says that land development regulations can dictate how septic systems "must be installed as a condition precedent to the approval of" a land development plan.[124] Although installation is but one of many areas of septic system regulation, this language could be interpreted as affirming at least some local authority to directly regulate septic systems. Overall, it seems likely that South Carolina local governments may not be preempted from adopting ordinances directly regulating the use of septic systems.

6.4 Regulatory barriers

6.4.1 Nags Head

Since 2000, Nags Head, N.C., has had one of the most comprehensive non-regulatory septic management programs in the U.S. The town's Septic Health Initiative uses a combination of incentives (e.g. free inspections, water bill rebates for system pumping, low-interest loans for system repairs or replacements), water quality monitoring, and education to promote sound septic system management in the community. Sewer service is unavailable in Nags Head, and construction of a wastewater treatment plant to serve the community is financially and regulatorily challenging. Replacing private septic systems with publicly owned infrastructure could also expose the Town to increasing maintenance costs and risk of liabilities as seas continue to rise.

In recent years, various initiatives have identified a number of additional policies and programs for potential implementation in Nags Head to improve the function of septic systems. These policies can be grouped into regulatory, non-regulatory, and infrastructure development actions. We group the specific actions below, followed by a brief analysis of regulatory barriers or challenges for each group.

Regulatory:

- Mandatory septic inspection program[125]
- Higher standards for separation between drainfields and water table[126]
- Development of a more robust decentralized wastewater management plan based on the US EPA's Voluntary National Guidelines for Management of Onsite and Clustered (Decentralized) Wastewater Treatment Systems (specifically, along the lines of Management Models 2 and 3 – the maintenance contract and operating permit models, respectively)[127]

As described in our preemption analysis above, it is likely that North Carolina local governments are preempted from directly regulating the use of septic systems. There is nothing preventing Nags Head from adopting any of the regulatory programs listed above, but if a lawsuit was brought challenging Nags Head's authority to regulate in this area, the programs could be struck down by a court. It is worth noting, however, that communities do sometimes adopt programs they know may be challenged in order to bring attention

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[123] S.C. Code Ann. § 44-1-140(11) (2022).

[124] S.C. Code Ann. § 6-29-1130(B) (2022).

[125] Recommended by *Adaptation Planning in the Town of Nags Head: Vulnerability, Consequences, Adaptation, Planning Scenarios (VCAPS) Report* (NC Sea Grant 2017).

[126] *Id.*

[127] Recommended by *Town of Nags Head, North Carolina, Decentralized Wastewater Management Plan 2022 DRAFT.*

to an important matter to state legislators. A high profile lawsuit highlighting the issue of adapting the use of septic systems to climate change could prompt state legislators to take action on the subject.

Another option for Nags Head is to encourage the Dare County Health and Human Services Board to request permission from the state to adopt more stringent regulations. Under North Carolina law, local boards of health may petition the state to adopt more stringent regulations for septic systems.[128] As local boards of health are appointed by county commissions in North Carolina, this option could require communication and coordination with the Dare County Board of Commissioners.

Non-regulatory:

- Maintain and expand the Septic Health Initiative[129]
- Development of a voluntary septic subscription service (a septic utility)[130]
- Enhance existing public education and outreach campaign[131]

Non-regulatory programs would not be preempted by state law, so Nags Head would be free to engage in these activities. It will, however, behoove the town to carefully think through ways to craft the program to avoid exorbitant costs or unanticipated liabilities. Issues could arise if the town did not adequately factor in impacts from climate change when establishing levels of service. It could, for example, find itself responsible for funding more system repairs or replacements than it had anticipated if systems in vulnerable areas in the program began to fail because of rising water tables. In addition, a major storm event or other situation that necessitates repairing or replacing many systems in the program within a short period of time could be an issue and expose the town to liability. These issues could be avoided by excluding systems in certain highly vulnerable areas from the program, limiting coverage of repairs to a maximum dollar amount, only covering maintenance and small repairs, or limiting coverage involving major storm events.

Infrastructure development:

- Utilize offsite septic and/or shared/cluster systems for small neighborhoods[132]
- Replace conventional septic with mound systems in certain areas[133]

Without additional context, the regulatory barriers for these infrastructure development activities cannot be certain. It is possible that either could be accomplished through entirely voluntary or incentive-based approaches. If they were attempted via regulation, they could be preempted by state law. Indeed, North Carolina law specifically prohibits municipalities from regulating the use of off-site wastewater systems.[134]

[128] N.C. GEN. STAT. § 130A-335(c2) (2022).

[129] Recommended by *Town of Nags Head, North Carolina, Decentralized Wastewater Management Plan 2022 DRAFT.*

[130] *Id.*

[131] *Id.*

[132] Recommended by *Adaptation Planning in the Town of Nags Head: Vulnerability, Consequences, Adaptation, Planning Scenarios (VCAPS) Report* (NC Sea Grant 2017).

[133] Recommended by *Stormwater Pilot Project for NCDOT Maintained Ocean Outfalls and Associated Outlets: Ocean Outfall Master Plan* (NC Dept. of Env. Quality 2016).

[134] N.C. Stat. §130A-335(c2) (2022).

6.4.2 Folly Beach

The regulatory barriers faced by Folly Beach are less a matter of local authority – as noted above, it is less likely that South Carolina local governments are preempted from directly regulating septic systems, and Folly Beach has adopted regulations on septic[135] – and more a matter of information gaps caused by regulatory interpretation. In many ways, Folly Beach has relied on septic systems as a form of land use and development control. Sewer service is available to the community – the Plum Island treatment plant has sufficient capacity for the entire city to be sewered – but there has been little desire to connect, fueled at least in part by a fear that sewer would result in the development of large condominiums and other developments out of character with the low density city known as "The Edge of America."

Concerns about climate change and sea level rise have, however, prompted the city to think about septic systems with more scrutiny. In its 2017 Sea Level Rise Adaptation Report, a Septic Vulnerability Assessment is listed as a recommended adaptation action. The report recommends mapping and inventorying all septic systems on the island to "track failures, site use, age of system, size of tank, location of system in relation to surface waters, etc."[136]

Folly Beach officials are interested in conducting such an inventory of septic systems to inform decisions on extending sewer service or adopting other adaptation measures. In communities in other states, basic inventories can be conducted through a simple permit review, which can provide information such as the number of septic systems in a given area, system ages, types, and, if maintenance and repair information is included in records, system condition. In South Carolina, however, a septic system inventory will be more challenging because the state agency that regulates the installation of septic systems destroys all septic permits that were issued more than five years ago. This practice is based on a curious interpretation of a state regulation that limits the validity of septic system installation permits to five years.[137] Officials with the SCDHEC interpret this regulation to mean that they must dispose of all septic installation permits after five years, *even for systems that have already been installed.*[138] Without a permit record, it is virtually impossible to know whether any individual septic system over five years old was legally installed under a valid permit from SCDHEC. Certificates of occupancy from local governments may require proof of a valid SCDHEC install permit, but a new system could be installed after the certificate of occupancy was issued. In addition, SCDHEC does not automatically require permits for system repairs (whether a permit is required is left up to the local official's discretion[139]). South Carolina rules concerning septic systems do not require system maintenance, so system condition cannot be gleaned from maintenance records, either. In essence, in South Carolina communities without local rules on septic systems that require permits or maintenance activities, local officials who want to gauge the condition of septic systems and their potential impacts on public and environmental health must engage in much more intensive inventory programs that include

[135] In 2019, the city of Folly Beach adopted a new chapter to its code of ordinances concerning onsite septic system management. Among other things, these rules made important changes to siting requirements and require system inspections. New septic systems in Folly Beach must be sited "as landward as possible," and building permits will not be issued for structures where the proposed septic location is within a dune management area. Inspections are required prior to the sale of a home, after a repair due to a system failure, and annually for all short-term rentals. Folly Beach, SC, Code of Ordinances, Ch. 55 (2022).

[136] *City of Folly Beach, South Carolina, Sea Level Rise Adaptation Report* 16 (2017).

[137] S.C. REGS. § 61-56.103.2(3) (2022).

[138] Phone interview with Tim Stanley, Program Manager, Onsite Wastewater Unit, Bureau of Environmental Health Services, South Carolina Department of Health and Environmental Control, Feb. 2022.

[139] S.C. REGS. § 61-56-.104.2(1) ("The Department *may* also require a permit to construct and approval to operate for the repair … of an onsite wastewater system … when deemed necessary…" (emphasis added)).

individual system inspections and will be significantly more expensive than a permit record review. For communities like Folly Beach that must assess the potential impacts of climate change on septic systems, this makes such analyses that much harder and costlier.

6.5 Workable policy approaches

6.5.1 Nags Head

Project personnel attended Nags Head's Decentralized Wastewater Management Plan Update committee meetings as technical experts. We provided information on utility programs in other states, among other things. The Plan was finalized in spring of 2022, and Town officials have asked project personnel to serve on a Working Group for developing one of the Plan's selected policy activities - a voluntary septic utility program. We will provide guidance on how to properly incentivize participation while incorporating information from our technical research and mechanisms for mitigating cost overruns and liabilities related to sea level rise.

6.5.2 Folly Beach

Project personnel clarified SCDHEC's interpretation of its permit retention policy for Folly Beach officials. The city has expressed a desire for a plain language report detailing our technical findings, plus guidance on how to conduct system inventories in the city in the absence of permit records. We are developing these documents now.

7. Economic prioritization of municipal investment in OWTS

By Eric Edwards, Ph.D. and Iain Burnett, Dept. of Agricultural and Resource Economics, NC State University

Economics is a discipline dedicated to understanding the allocation of scarce resources. We use marginal economic analysis—an examination of the incremental benefits of an activity compared to the incremental costs incurred—to provide a framework for communities to make the most of limited budgets to improve pollution due to onsite wastewater treatment systems (OWTS).

Throughout this discussion we will use the Town of Nags Head, N.C. as an example of the challenges faced in making wastewater infrastructure investments. Nags Head is considering many potential approaches to addressing water contamination issues attributed to onsite septic systems. The Town is in the process of finalizing a decentralized wastewater management plan to guide future investments, with an emphasis on education, inspections, maintenance, and monitoring.[140] In implementing their plan, Nags Head must decide how much to invest in each measure, which locations or types of systems to prioritize, and how to assess progress towards their climate adaptation goals. Our goal in this work is to elucidate a step-by-step process that any household or municipality could use to cost-effectively reduce environmental and groundwater pollution due to OWTS.

7.1 Economic benefits of managing OWTS

The economic benefits associated with addressing water pollution can be substantial. Beyond the intrinsic value of being good environmental stewards, there are explicit financial benefits to effective OWTS and lower pollution related to tourism, property values, and environmental health. The following studies show just a few of the widespread benefits that accrue from managing environmental water pollution:

- A study from Cape Cod found that "pristine" public beaches with no history of water quality closures are worth more than double the value to visitors and local economies relative to similar beaches that had been closed at least once due to water quality issues.[141]
- Chesapeake Bay coastal houses saw sale prices positively correlated with total maximum daily load-related improvements in bay water clarity, a premium of up to 1.2% per property.[142]
- Waterfront properties in Rhode Island, Maryland, and Massachusetts saw sale price premiums of 13% to 19% for houses with advanced OWTS versus baseline conventional OWTS, while houses with municipal sewer hookups saw a 5% premium over non-sewered properties.[143]

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[140] https://www.nagsheadnc.gov/1035/Decentralized-Wastewater-Management-Plan

[141] Lyon, Sarina F.; Merrill, Nathaniel H.; Mulvaney, Kate K.; and Mazzotta, Marisa J. (2018) "Valuing Coastal Beaches and Closures Using Benefit Transfer: An Application to Barnstable, Massachusetts," Journal of Ocean and Coastal Economics: Vol. 5: Iss. 1, Article 1. https://doi.org/10.15351/2373-8456.1086

[142] Klemick, H., Griffiths, C., Guignet, D., & Walsh, P. (2016;2018;). Improving water quality in an iconic estuary: An internal meta-analysis of property value impacts around the chesapeake bay. Environmental & Resource Economics, 69(2), 265-292. https://doi.org/10.1007/s10640-016-0078-3

[143] CoreLogic. Impact of Advanced Septic Installation and Sewer Connection on House Prices. Report prepared for Suffolk County, NY. Updated March 2020

- A study in the Mediterranean showed that the greatest environmental benefit of effective water treatment was for wetlands, which are most sensitive to eutrophication. In 2022 prices, the monetary benefit of removing one kilogram of nitrogen is $86.16.[144]

7.2 Economic framework

The basis of our approach is to estimate marginal abatement costs, which is useful for comparing approaches to reduce pollution when a complex set of solution options exist.[145] Marginal abatement cost analysis provides a clear comparison of the marginal benefits and costs of different solutions, giving local leaders and policymakers insight into key tradeoffs.

In the context of environmental pollution, there are three primary abatement strategies: 1) reduce input, or "change in process," 2) improve storage and treatment, or "end of pipe" and 3) clean up what gets out.[146] For this report we will focus primarily on improving treatment, while briefly providing ideas on how to reduce input. However, all three strategies are valid and should receive consideration.

Generally, there are five steps to follow for analyzing marginal abatement.

1. Identify pollutant(s) of interest and all relevant sources of pollution for abatement.
2. Collate available abatement techniques, including legacy systems or ones in development.
3. Calculate costs and abatement potential for each technique.
4. Standardize data for marginal abatement cost, e.g. dollars per one additional unit of pollution prevented.
5. Plot the cost against the amount of abatement for each technique.

7.3 Cost-effective investment in OWTS

We approach this problem for the Town of Nags Head, N.C., with the goal of reducing Total Nitrogen reaching groundwater and surface water. We follow the steps from the preceding section to analyze marginal abatement costs for a representative household. For brevity we report just an overview of the approach with results. Full details, derivations, and background references can be found in our standalone report.[147]

Step 1: For clarity, we focus on nitrogen sources from residential OWTS. This analysis may be applied to phosphorus, pathogens, or any combination of pollutants deemed critical to control. In this example, Nags Head backs up to Roanoke Sound and Albemarle Sound, where nitrogen-induced eutrophication is a concern.

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[144] Hernández-Sancho, F., Molinos-Senante, M., & Sala-Garrido, R. (2010). Economic valuation of environmental benefits from wastewater treatment processes: An empirical approach for spain. The Science of the Total Environment, 408(4), 953-957. https://doi.org/10.1016/j.scitotenv.2009.10.028

[145] Kesicki, F., & Strachan, N. (2011). Marginal abatement cost (MAC) curves: Confronting theory and practice. Environmental Science & Policy, 14(8), 1195-1204. https://doi.org/10.1016/j.envsci.2011.08.004

[146] Beaumont, N. J., & Tinch, R. (2004). Abatement cost curves: A viable management tool for enabling the achievement of win–win waste reduction strategies? Journal of Environmental Management, 71(3), 207-215. https://doi.org/10.1016/j.jenvman.2004.03.001

[147] Edwards, E. C. & Burnett, I. (2022). Coastal onsite wastewater treatment systems: prioritizing investment through abatement cost analysis. North Carolina State University Report.

Step 2: After studying available literature and expert recommendations, we identified key categories of relevant abatement techniques which we summarize below. Except for municipal wastewater treatment plants, all system types are still in use in Nags Head.

Cesspool / Straight Discharge System

One of the earliest and simplest OWTS is a cesspool, defined as an unsealed holding tank that household waste flows into, solids and fats separate, and effluent percolates vertically or laterally into the ground. Straight discharge systems are similar, where effluent leaves the holding tank through an outlet pipe and flows into a nearby ditch or waterbody. Treatment is usually inefficient and both systems are still relatively prevalent in the United States.[148]

Conventional System

Where conditions are appropriate, conventional onsite wastewater treatment systems are a cost-effective choice. These systems typically include a separation tank with a gravity-fed drainfield filled with native soils, sand, stone, gravel, or other porous media. They are relatively simple to maintain and represent the minimum standard for new construction and cesspool upgrades.

Advanced System

These systems typically offer better pollutant capture and reduction capabilities than conventional systems, and their flexibility and efficiency make them useful for problematic locations or environmentally sensitive areas. Examples of appropriate options for nitrogen reduction include media filters (e.g., sand, peat, textile fabric, gravel) with recirculation and/or addition of external carbon supplies; and fill or mound systems with pressure dispersal that incorporate carbon-rich media for nitrification and denitrification. These systems typically use automated technology and need frequent maintenance for optimal performance.

Advanced System: Cluster or Package Plant

These systems provide advanced wastewater treatment for a group of houses. Typically, each house uses an effluent pump or grinder pump system to convey their wastewater to the nearby treatment system. Appropriate options for nitrogen reduction include activated sludge / aerobic treatment units; recirculating media filters; and sequencing batch reactors. These systems typically use automated technology and need frequent maintenance for optimal performance. These systems may require multiple acres of vacant land to host the treatment system and communal drainfield.

Municipal Wastewater Treatment Plant

Municipal wastewater treatment plants (WWTP) can handle an entire town or region’s wastewater and are often paired with gravity sewers to receive wastewater from area houses and businesses. These systems are often designed around activated sludge or aerobic treatment unit technology, biological nutrient removal, and sand filtration polishing unit technology. They generally discharge treated effluent directly into a nearby waterbody.

Step 3: We calculate total costs and total nitrogen abatement potential for each household for a 30-year system lifetime. Costs are adjusted to 2022 values and local market conditions to allow for a direct comparison. Total costs represent the net present value (NPV) of initial capital for the treatment system,

[148] Greywater systems are designed similar to straight discharge systems, generally with less influent loading of nutrients, pathogens, and chemicals. For this class of systems, treatment efficiency largely depends on soil type and soil depth to groundwater.

conveyance technology, and land in year 0, plus annual O&M that includes maintenance, repairs, inspections, and energy use in years 1-30. We use a 5% discount rate and omit any interest or fees related to financing. Lifetime costs are presented in Table 7.1 with point estimates and likely ranges, plus any required land.

Table 7.1. System Cost Summary, Per Household over 30-Year Lifetime.[149]

	30-Year Household Cost (NPV, 2022 USD)	Initial Capital Cost (2022 USD)	30-Year O&M Cost (NPV, 2022 USD)	Communal Land (acres)
Cesspool (1 House)	Estimate: **$1,537** Range: $922 - $9,223	N/A	Estimate: $1,537 Range: $922 - $9,223	N/A
Conventional (1 House)	Estimate: **$9,806** Range: $4,922 - $26,992	Estimate: $7,500 Range: $4,000 - $17,000	Estimate: $2,306 Range: $922 - $9,992	N/A
Advanced (1 House)	Estimate: **$32,761** Range: $16,149 - $54,447	Estimate: $22,000 Range: $10,000 - $36,000	Estimate: $10,761 Range: $6,149 - $18,447	N/A
Advanced Cluster (10 Houses)	Estimate: **$71,501** Range: $40,054 - $102,634	Estimate: $57,820 Range: $33,290 - $82,650	Estimate: $13,681 Range: $6,764 - $19,984	Estimate: 0.5 Range: 0.3 - 0.7
Advanced Cluster (20 Houses)	Estimate: **$68,221** Range: $38,194 - $96,344	Estimate: $54,540 Range: $31,430 - $76,360	Estimate: $13,681 Range: $6,764 - $19,984	Estimate: 1.0 Range: 0.5 - 1.4
Advanced Cluster (100 Houses)	Estimate: **$56,491** Range: $29,324 - $88,644	Estimate: $42,810 Range: $22,560 - $68,660	Estimate: $13,681 Range: $6,764 - $19,984	Estimate: 3.4 Range: 1.8 - 4.7
Advanced Cluster (250 Houses)	Estimate: **$31,891** Range: $18,854 - $45,455	Estimate: $18,210 Range: $12,090 - $25,471	Estimate: $13,681 Range: $6,764 - $19,984	Estimate: 0.5 Range: 0.3 - 0.7
Municipal WWTP (5280 Houses)	Estimate: **$28,549** Range: $22,071 - $39,464	Estimate: $12,100 Range: $8,851 - $19,634	Estimate: $16,449 Range: $13,220 - $19,830	Estimate: 8 Range: N/A

Abatement potential represents the difference between a starting point and potential ending point, and thus we need to consider total nitrogen effluent output and reduction for all combinations of initial and end conditions. For this analysis, we assume household population to be a constant 2.5 persons year-round and that each person has a steady influent loading rate of 5.7 kg-N/person-year.[150] We consider "do nothing" as the baseline for abatement potential. The results are presented in Table 7.2.

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149 All systems noted use drainfields for final effluent treatment and dispersal, with exception of the 250 House Cluster and Municipal WWTP where direct discharge is used. Initial capital costs are based on "as built" case studies in communities representative of our study area; for cluster systems this includes household effluent or grinder pump systems, and for wastewater treatment plants this includes sanitary distribution networks, pump stations, and outfalls.

150 O'Driscoll, M. A., Humphrey, C. P., Deal, N. E., Lindbo, D. L., & Zarate-Bermudez, M. A. (2014). Meteorological influences on nitrogen dynamics of a coastal onsite wastewater treatment system. Journal of Environmental Quality, 43(6), 1873-1885. https://doi.org/10.2134/jeq2014.05.0227

Table **7.2**. Total Nitrogen Effluent Totals and Abatement Potential, 30-Year Lifetime for Representative Household.[151]

Starting Point	Ending Point				
	Baseline	**Conventional** 256.5 kg-N Output	**Advanced** 106.9 kg-N Output	**Advanced: Cluster** 85.5 kg-N Output	**Municipal WWTP** 42.8 kg-N Output
Cesspool	427.5 kg-N Output 0 kg-N Abated	171.0 kg-N Abated	320.6 kg-N Abated	342.0 kg-N Abated	384.8 kg-N Abated
Conventional: Problematic	342.0 kg-N Output 0 kg-N Abated	85.5 kg-N Abated	235.1 kg-N Abated	256.5 kg-N Abated	299.3 kg-N Abated
Conventional: Functional	256.5 kg-N Output 0 kg-N Abated		149.6 kg-N Abated	171.0 kg-N Abated	213.8 kg-N Abated
Advanced	106.9 kg-N Output 0 kg-N Abated			21.4 kg-N Abated	64.1 kg-N Abated
Advanced: Cluster	85.5 kg-N Output 0 kg-N Abated				42.8 kg-N Abated

Step 4: We standardize the data from Step 3 to calculate the pollution abatement costs of adopting a particular technology (top row), given some starting technology (left column). This cost is reported in dollars per kilogram of total nitrogen abated ($/kg-N) using a 30-year lifetime for the new technique adopted. For completeness we also show the low and high estimates for costs based on the lifetime cost ranges we derived in Step 3. The results are below in Table 7.3.

Table 7.3. Abatement Costs ($/kg-N) for a Representative Household Over 30-Year Lifetime (Low and High Range in Parentheses).

End **Start**	Conventional	Advanced	Advanced Cluster (10 Houses)	Advanced Cluster (20 Houses)	Advanced Cluster (100 Houses)	Advanced Cluster (250 Houses)	Municipal WWTP (5280 Houses)
Cesspool	**$57.35** (28-157)	**$102.18** (50-169)	**$209.07** (117-300)	**$199.48** (111-281)	**$165.18** (85-259)	**$93.25** (55-132)	**$74.20** (57-102)
Conventional: Problematic	**$114.69** (57-315)	**$139.33** (68-231)	**$278.76** (156-400)	**$265.97** (148-375)	**$220.24** (114-345)	**$124.33** (73-177)	**$95.40** (73-131)
Conventional: Functional		**$218.95** (107-363)	**$418.13** (234-600)	**$398.95** (223-563)	**$330.36** (171-518)	**$186.50** (110-265)	**$133.56** (103-184)
Advanced			**$3,345.08** (1873-4801)	**$3,191.63** (1786-4507)	**$2,642.85** (1371-4147)	**$1,491.98** (882-2126)	**$445.21** (344-615)
Advanced: Cluster							**$667.81** (516-923)

[151] Total Nitrogen reduction efficiencies used for this analysis are: Cesspool (0%), Conventional: Problematic (20%), Conventional (40%), Advanced (75%), Advanced: Cluster (80%), Municipal WWTP (90%). Poor performance for Cesspools and Conventional systems are largely a result of sandy soils and high groundwater tables in the study area. Research focused on systems in the coastal Carolinas found lower Total Nitrogen reduction efficiencies for advanced cluster systems (77%) and municipal WWTP (83% reduction).

Step 5: In **Figure 7.1** we present abatement costs for a representative household. For clarity, we show one set of possible solutions given each starting point to highlight the differences in abatement potential (x-axis) and abatement cost (y-axis) for each end point. Error bars show the likely range for each cost. We acknowledge that a conventional system may be inappropriate for some lots due to soil types or high groundwater tables.

From Steps 3 and 4, we learned that upgrading an existing advanced system offers little abatement potential, and results in high absolute and marginal costs. From any starting point, upgrading to small cluster systems has relatively high costs due primarily to the capital needed to secure vacant land in Nags Head, and the inefficient land use that arises from small cluster systems due to drainfield setback requirements. In general, addressing cesspools and problematic conventional systems provides the largest abatement potential at the lowest overall marginal abatement cost.

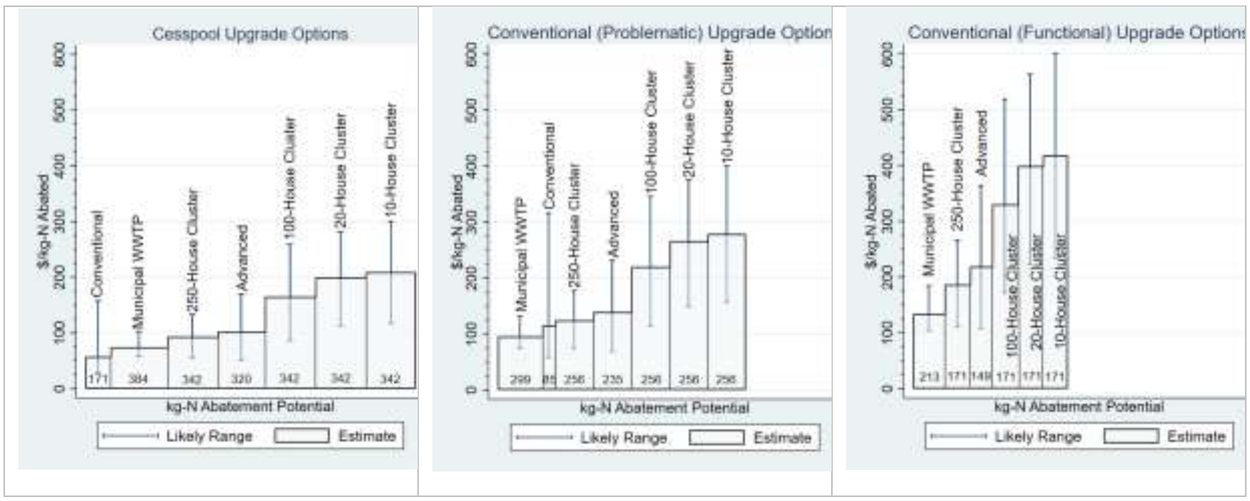

Figure 7.1. Abatement costs for three starting points. The bar width represents proportional abatement potential, and the inset number indicates the absolute kg-N abatement potential for that particular upgrade option, given a starting condition. For example, in the leftmost figure (Cesspool Upgrade Options), we can see that adopting a Conventional system would provide 171 kg-N abatement (from **Table 7.2**) at an abatement cost of $57.35 / kg-N (from **Table 7.3**); the error bars indicate that depending on the particular house site and project requirements, a realistic abatement cost range is $28 / kg-N to $157 / kg-N.

Our other case study site in Folly Beach, South Carolina has similar land values, and construction costs approximately 4% to 12% higher than Nags Head; lifetime O&M costs are likewise similar. This means that the results presented here are approximately accurate for the City of Folly Beach.

7.4 Example use of marginal abatement cost analysis

We can use a hypothetical example to demonstrate how the insight from abatement cost analysis can aid in decision making.

There are 20 houses in a waterfront where residents notice that water adjacent to their community is often murky and fish are rarely caught from the dock. Regular water tests find high nitrogen and low dissolved oxygen levels consistent with eutrophication. Based on these results, an expert consultation determines that if the neighborhood can abate at least 165 kg-N per year, water quality will improve to acceptable levels. Permit reviews show that 10 of the houses have conventional systems and 10 older homes have cesspools. An inspection reveals that 5 of conventional systems are problematic and not working as designed. The city agrees to fund investment in upgrades through one of its grant programs, but there is debate over what to fund.

One manager suggests putting in a 20-house cluster system. Looking at the abatement costs for the cesspool homes: 10 houses each abate 11.4 kg-N annually at a cost of $199 / kg-N; 5 houses have problematic conventional systems and each abate 8.5 kg-N annually at a cost of $266 / kg-N; 5 houses with operational conventional systems each abate 5.7 kg-N at a cost of $399 / kg-N. Under this solution the homeowners can reduce total N runoff by 185 kg-N per year.

Another manager suggests upgrading homes to individual advanced systems: 10 cesspools upgrade for $102 / kg-N, each reducing N by 10.6 kg annually. The problematic conventional systems are upgraded for a cost of $139 / kg-N, each reducing N by 7.8 kg annually. The working conventional system upgrades costs $219 / kg-N, each reducing N by 5.0 kg annually. The total annual reduction of 170 kg-N comes at a substantially lower marginal cost.

This lower marginal cost of abatement suggests substantial savings from the second manager's plan. It provides the city with the opportunity to invest in alternative abatement approaches at a much lower cost. Marginal analysis of the difference in the two plans suggests the 20-house cluster system generates 15 kg-N additional annual abatement, relative to the second manager's plan, but the city is paying $399 per kg-N removed for these last units of abatement. This money could be better spent on other upgrades. For instance, investing instead in upgrading homes with cesspools in other neighborhoods to advanced systems would yield four times the N abatement per dollar spent.

7.5 Additional low-cost behavior changes

Previously, we identified reduced input or "change in process" as the first strategy in pollution abatement. Here we propose behavioral changes that can reduce groundwater and environmental nutrient loading. While we do not quantify the cost-effectiveness of these behavioral interventions, they can be implemented cheaply and may yield substantial pollution reductions relative to their costs.

1. Overloaded drainfields can increase pollution. Showing septic capacity on consumer water bills can provide homeowners a comparison of their average daily water use and the septic design rate for their septic system (generally 120 gallons/bedroom-day in North Carolina).[152] If specific data exists, municipal water utilities can flag water bills that indicate potential overuse. Smart water meters tracking indoor usage can also provide instant feedback on overuse days; these cost around $200 and reduce water use by an average of 19.6%.[153]
2. Many homeowners list their coastal homes as rentals, and renters may be unaware that the home is on a septic system. A search of Airbnb for Nags Head rental homes found that 132 of 261 rentals advertised greater capacity than the number of bedrooms would indicate, by an average of 2.3 people above capacity.[154] Informal reminders of septic capacity to all homeowners and notices in rental properties for renters can reiterate that water use should be limited.

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[152] North Carolina Onsite Wastewater Rules SECTION .1900 - SEWAGE TREATMENT AND DISPOSAL SYSTEMS. (2017) https://ehs.ncpublichealth.com/oswp/docs/rules/1900-Rules-08-2017.pdf

[153] Sønderlund, A. L., Smith, J. R., Hutton, C., & Kapelan, Z. (2014). Using smart meters for household water consumption feedback: Knowns and unknowns. Procedia Engineering, 89, 990-997. https://doi.org/10.1016/j.proeng.2014.11.216

[154] Airbnb Nags Head Vacation rentals. (2022, February 12). https://www.airbnb.com/nags-head-nc/stays

3. High tides or a storm surge can raise groundwater tables with very little time lag, and at-risk drainfields can mix with groundwater.[155] Extreme precipitation can increase transport and lead to higher absolute values of nutrients and increased ammonium concentrations reaching the environment.[156] A reminder to homeowners to go easy on their septic system when extreme rain or high tide events are forecasted may reduce environmental pollution.
4. Garbage disposals can increase OWTS effluent total nitrogen by 2.5% and total phosphorus by 5.7%.[157] Communities can educate and incentivize homeowners to remove their garbage disposals or dispose of most food scraps in garbage or compost bins.

7.6 Addressing other causes of water pollution

While the focus of this work is reducing the pollution impacts of OWTS, it is important to consider all potential causes of water pollution, especially those that may be reduced at low cost. High nitrogen, phosphorus, or pathogen levels in drainage ditches or stormwater runoff could be caused by domestic fertilizer use, animal waste, or yard waste. If the pollution source is not entirely OWTS, then upgrading these systems will not fully reduce pollution to desired levels. These studies illustrate the potential magnitude of "invisible" pollution that can be found in a typical community:

1. Dog waste is a significant source of nitrogen, phosphorus, and pathogens, and is often left on the ground.[158] Communities can launch pet waste awareness campaigns, provide waste cans and bag stations in strategic locations, and lightly irrigate pathways or dog parks to let grass use up free nitrogen before it washes out in rainfall.
2. Grass clippings are 4% nitrogen, and a 1000 ft^2 lawn can produce ~5.44 kg-N/year.[159] Encouraging municipal yard waste disposal or compost bins can reduce runoff nitrogen loading.
3. Coastal communities can use drainage ditch treatments to strategically reduce nutrient loading in runoff outflows. Drainage ditch bioreactors, a natural filter made with woodchips and gravel, can reduce runoff nitrates from landscaping or agriculture by 65% at an average cost of $41 / kg-N removed.[160] These require regular maintenance if subject to sedimentation.

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[155] Kim, J., Lee, J., Cheong, T., Kim, R., Koh, D., Ryu, J., & Chang, H. (2005). Use of time series analysis for the identification of tidal effect on groundwater in the coastal area of kimje, korea. Journal of Hydrology (Amsterdam), 300(1), 188-198. https://doi.org/10.1016/j.jhydrol.2004.06.004

[156] Mallin, M. A. (2013). 4 - septic systems in the coastal environment: Multiple water quality problems in many areas. Monitoring water quality (pp. 81-102). Elsevier B.V. https://doi.org/10.1016/B978-0-444-59395-5.00004-2
O'Driscoll, M. A., Humphrey, C. P., Deal, N. E., Lindbo, D. L., & Zarate-Bermudez, M. A. (2014). Meteorological influences on nitrogen dynamics of a coastal onsite wastewater treatment system. Journal of Environmental Quality, 43(6), 1873-1885. https://doi.org/10.2134/jeq2014.05.0227

[157] Lin, H., Wang, Y., van Lierop, L., Zamalloa, C., Furlong, C., Keleman, M., & Hu, B. (2019). Study of food waste degradation in a simulated septic tank. Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA, 37(12), 1199–1206. https://doi.org/10.1177/0734242X19879221

[158] De Frenne, P., Cougnon, M., Janssens, G. P. J., & Vangansbeke, P. (2022). Nutrient fertilization by dogs in peri-urban ecosystems. Ecological Solutions and Evidence, 3(1), n/a. https://doi.org/10.1002/2688-8319.12128

[159] Starbuck, J. (1999). Grass Clippings, Compost and Mulch: Questions and Answers. https://extension.missouri.edu/media/wysiwyg/Extensiondata/Pub/pdf/agguides/hort/g06958.pdf

[160] Christianson, L. E., Collick, A. S., Bryant, R. B., Rosen, T., Bock, E. M., Allen, A. L., Kleinman, P. J. A., May, E. B., Buda, A. R., Robinson, J., Folmar, G. J., & Easton, Z. M. (2017). Enhanced denitrification bioreactors hold promise for Mid-Atlantic ditch drainage. Agricultural & Environmental Letters, 2(1), 1-5. https://doi.org/10.2134/ael2017.09.0032

7.7 Roadmap

The following roadmap can serve as a guide to community leaders seeking to invest in OWTS improvements. Engagement with local educational institutions and non-profits, public employees in civil engineering, health, and utilities, and technical services contractors will improve planning and implementation.

1. Identify the key parameters. Ideally, overlay the following information onto a GIS map or other presentable format to identify patterns and see the big picture, including high risk locations.
    a. Identify pollutant(s) your community is trying to mitigate: COD, BOD, nutrients, microbes, or pharmaceuticals.
    b. Understand your local hydrology. This includes groundwater depth, surface water features, drainage ditches, and outflow locations. Mark particularly sensitive locations where aquatic life or human health are at significant risk from pollution.
    c. Know the current state of OWTS for all local properties. This includes their location (especially the drainfield), usage patterns, system design, system age, and efficacy.
    d. Forecast the impacts of climate change. Rising seas, increased precipitation and flooding, and groundwater tables will impact local OWTS.
2. Understand the current state of pollution. This preliminary work is critical for laying the foundation for your strategy and implementation plan. Sample monthly, plus during extreme events (heavy rain, tides/surges, and droughts). Preliminary sampling should last multiple years to ensure results are representative.
    a. Monitor groundwater depth and drainage flows at multiple locations.
    b. Sample groundwater and drainage water for key pollutants.
3. Use the abatement cost framework to understand tradeoffs in mitigating pollution to specific levels (e.g., state or federal water quality standards, or environmental thresholds).
    a. Pollutants are the issue, and the goal is to seek lowest cost pollution mitigation first. This may be a mix of property specific OWTS improvements, community-wide conservation and efficiency efforts, and public infrastructure changes.
    b. Identify the local benefits of managing pollution; these benefits justify investments and help get the community on board.
4. With community and stakeholder buy-in, decide on a priority list for improvements based on risk factors and other pertinent considerations. Benefits and costs should be explicit, and the project should be politically viable over its expected duration.
    a. Property risk factors should account for climate change effects over a 30-year forecast.
    b. To engage community support for a municipal WWTP, share case studies from similar communities that completed septic-to-sewer conversions, and develop local conversion plans.[161]
5. Continue to monitor groundwater and surface water quality for the lifetime of the project, and adjust implementation plan as needed.
    a. Reevaluate the abatement cost distributions and abatement potentials as new OWTS technologies become practicable, as costs change, or as regulations are updated.

[161] Warner, L. A., Krimsky, L. S., & Rampold, S. D. (2022). Using a diffusion of innovation lens to understand homeowner support for septic system to sewer system conversions. *Journal of Environmental Management*, *319*, 115651.

The journey of a thousand miles begins with one step. While the work plan outlined above is substantial, arriving at the best solution the first time around will be worth the due diligence. Many coastal and waterfront communities have already begun the process of OWTS management as a means of pollution mitigation, and much can be learned by reaching out for advice.