NC STATE UNIVERSITY

Coastal Onsite Wastewater Treatment Systems: Prioritizing Investment through Abatement Cost Analysis

Dr. Eric C. Edwards[1]
Assistant Professor and Extension Specialist
Department of Agricultural and Resource Economics
North Carolina State University

Iain Burnett
Masters Student
Department of Economics
North Carolina State University

[1] This project was funded by the NOAA Climate Program Office (NOAA-OAR-CPO-2019-2005530). We thank Andrew Hutchens and Sydney Dodson for their research assistance and Kylie Shephard, Holly White and the Town of Nags Head for sharing data and ideas. We thank our project team—Jane Harrison, Lauren Vorhees, Charles Humphrey, Michael O'Driscoll, Guy Iverson, Jared Bowden, and Katie Hill—for their feedback and help throughout this project.

Executive Summary

Coastal communities are intimately connected with the health of nearby waterbodies and ecosystems. A significant but sometimes overlooked portion of that connection is the interaction between the environment and residential onsite wastewater treatment systems (OWTS). These systems process household wastewater, which is loaded with nitrogen, phosphorus, pathogens, and other emerging contaminants such as surfactants and pharmaceuticals. While OWTS are essential, their decentralized nature can make addressing water pollution in a cost-effective manner a daunting task for elected leaders or municipal managers. In this report, we use an economic toolset to build a framework that any community can use to evaluate the benefits and costs of various infrastructure projects related to wastewater treatment.

We estimate the costs associated with all options for investment in OWTS. Our economic framework leads us to the following conclusions on the most cost-effective methods:

1. Legacy cesspools and straight discharge systems are prime candidates for upgrades that reduce the most pollution at the lowest cost.
2. Under a changing climate, conventional OWTS systems may fail. Identifying already failing systems or those most likely to fail through modeling and inspection will identify areas where investment in upgrades will lead to large pollution reductions at relatively low cost.
3. Municipal land for advanced cluster systems serving multiple houses can reduce a key cost and encourage the adoption of these high-performing systems.

We apply our framework the Town of Nags Head in North Carolina to illustrate the practical considerations facing managers in managing OWTS. This example illustrates the importance of data on OWTS and water pollution in making cost-effective investments. The cost estimates we provide are relevant to coastal communities throughout the southeastern United States. The report concludes with a roadmap for municipalities to follow to ensure cost-effective investment in OWTS to improve water quality and address ongoing concerns about sea-level and groundwater table rise resulting from climate change.

Table of Contents

Introduction

For coastal and waterfront communities that rely on decentralized wastewater systems, economic analysis can provide a framework for prioritizing solutions to excess water pollution. 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).

Infrastructure projects are complex, long-term investments that take years to complete, putting pressure on municipal decision makers to "get it right". Furthermore, fiscal prudence and political realities often dictate that communities try to achieve the most benefits for the lowest cost by picking the "low hanging fruit." When it comes to onsite wastewater treatment systems, efficacy and environmental pollution levels vary depending on multiple factors, and there is no simple formula to determine which OWTS are problematic and need improvement. Complicating the effort is that sea level rise and changing temperature and precipitation patterns can mean systems that are acceptable now may become problematic in the future.

Through this report 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 related 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. 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. To do so effectively, they need to perform an assessment of expected benefits and expected costs for every investment choice they make.

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.

Economic Benefits of Managing OWTS

The economic benefits associated with addressing water pollution can be substantial. There are concrete, estimable financial benefits to effective OWTS and lower pollution due to increased tourism, property values, and environmental health. The following studies offer examples of the widespread benefits that accrue from improving 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.[2]
- 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.[3]

---

[2] 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

[3] 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

- 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 properties without a sewer hookup.[4]
- A study in the Mediterranean showed that the greatest environmental benefit to effective water treatment was for wetlands, which are most sensitive to eutrophication, with the monetary benefit of removing one kilogram of nitrogen estimated at over $86.[5]

Economic Framework

The basis of our approach is to estimate marginal abatement costs (MAC), which is useful for comparing approaches to reduce pollution when a complex set of solution options exist.[6] Marginal abatement cost analysis provides a clear comparison of the marginal benefits and costs of different solutions, providing 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.[7] 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 unit of pollution prevented.
5. Plot the cost against the amount of abatement for each technique.

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.

---

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

[5] 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

[6] 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

[7] 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

Step 1: Identify Pollutants

Step 1: Identify pollutant(s) of interest and all relevant sources of pollution for abatement.

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.

Step 2: Analyze Abatement Techniques

Step 2: Collate all available abatement techniques, including legacy systems or ones in development.

After studying available literature and expert recommendations, we identified key categories of relevant abatement techniques based on initial system type and functionality.

Cesspool / Straight Discharge Systems

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. We note that greywater systems have designs 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.

Conventional Systems

Where conditions are appropriate, conventional onsite wastewater treatment systems are a cost-effective choice to remove nutrients from effluent. 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 Systems

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 or the 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 more frequent maintenance for optimal performance.

Advanced System: Cluster or Package Plants

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 or 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.

Except for municipal wastewater treatment plants, all system types are still in use in Nags Head.

Step 3: Calculate Abatement Costs

Step 3: Calculate costs and abatement potential for each technique.

We first calculate total costs for each household for a 30-year system lifetime. Lifetime costs represent the net present value (NPV) of initial capital for the treatment system, conveyance technology, and land in year 0, plus annual O&M that includes maintenance, repairs, inspections, and energy use in years 1-30. To simplify calculations, we excluded fees for surveying, engineering, permitting, and special lot preparations and note that these can be up to thousands of dollars depending on lot complexity.[8] To simplify marginal abatement cost calculations, we use our best judgement to create a point estimate for household costs for each system type and size and provide a range for likely costs.

For all studies referenced below, costs have been updated to 2022 values and adjusted to our study area in coastal North Carolina. For comparison over time, we use the US Bureau of Labor Statistics' CPI inflation calculator to adjust reference study costs given from January in the year of publication to January 2022.[9] Actual material and labor costs also vary due to local market conditions, and we use a "construction cost index" to compare project capital costs in the reference study location to Wilmington, NC using the 2021 cost index.[10] For costs taken from international studies, we use historical exchange rate tables and limit cost comparisons to nations where we perceive environmental and labor standards to be comparable.[11] Most costs presented are adjusted across location and time, or across exchange rate

[8] Verrecchia, J. (2018). The feasibility of septic systems for households in poverty in lee county, virginia. Journal of Appalachian Studies, 24(2), 223-235. https://doi.org/10.5406/jappastud.24.2.0223
[9] BLS (2022). CPI inflation calculator. https://www.bls.gov/data/inflation_calculator.htm
[10] RS Means (2021). City cost indexes – v2. https://www.rsmeans.com/media/wysiwyg/quarterly_updates/2021-CCI-LocationFactors-V2.pdf
[11] Federal Reserve (2022). Historical rates for the EU euro. https://www.federalreserve.gov/releases/h10/hist/dat00_eu.htm

and time, which introduces uncertainty and lowers the accuracy of our estimates. Where possible, we validate our estimated costs against local and recent costs.

We use a 5% discount rate when calculating lifetime costs and net present value given initial capital investment and ongoing O&M costs. One related study for a wastewater investment project in an environmentally sensitive area suggested a 5.5% rate.[12] A study evaluating government funded investment projects recommends a 7% discount rate rather than the commonly used 3% rate.[13] We also note that all costs are given at a household level, and interest or fees related to financing are omitted.

Our cost findings are summarized in Table 1 with point estimates and likely ranges for lifetime costs, capital including technology and land, annual O&M, and communal property required for systems and drainfields. Cost bases and considerations for each system are described below:

Table 1 System Cost Summary, Per Household over 30-Year Lifetime

	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

Cesspool / Straight Discharge System

Cesspools and straight discharge systems have limited efficacy and are often illegal for new construction, and so initial capital costs will be omitted from our analysis. However, they are still somewhat prevalent

[12] Djukic, M., Jovanoski, I., Ivanovic, O. M., Lazic, M., & Bodroza, D. (2016). Cost-benefit analysis of an infrastructure project and a cost-reflective tariff: A case study for investment in wastewater treatment plant in serbia. Renewable & Sustainable Energy Reviews, 59, 1419-1425. https://doi.org/10.1016/j.rser.2016.01.050
[13] Burgess, D. F., & Zerbe, R. O. (2013). The most appropriate discount rate. Journal of Benefit-Cost Analysis, 4(3), 391-400. https://doi.org/10.1515/jbca-2013-0016

for existing properties. One study in the Narragansett Bay watershed in Rhode Island found that 12% of OWTS are cesspools.[14] A North Carolina coastal community only recently upgraded from exclusively straight discharge systems that flowed directly into local estuary canals.[15]

Many states, including North Carolina, allow functional cesspools and straight discharge systems to remain in operation. In other states they are illegal or must be upgraded under certain conditions. Assuming some homeowners will choose to keep their cesspools in operation, O&M costs only include pumping to remove solids and fats from the holding tank. In a limited survey of Brevard County, Florida homeowners, mean pumping cost is $334 and median pumping cost is $251.[16] An evaluation of systems in Tampa, Florida estimated pumping cost at $436.[17] A recent survey of North Carolina and South Carolina septic system operators estimated pumping costs at $161 to $537.[18] Pumping frequency varies with the size of the holding tank and usage; given a 2.5 person house and typical 1000-gallon tank, every four years is safe with a likely range between six months and eight years.[19] For simplicity, we estimate annual pumping cost at $100 with a likely range of $60 to $600.

Conventional Systems

Conventional systems are very common and can account for the 70% or more of a community's OWTS.[20] Routine inspections often are not required for conventional systems, though some septic system pumpers will provide informal inspections during the course of a pump service. In the case of an OWTS malfunction, an inspection is typically the first step a homeowner takes. This is often a paid service with an average cost of $277, and approximately 40% of homeowners surveyed had their systems inspected in the prior four years.[21] For a typical home with one to four people, routine inspections of conventional systems are recommended at least every five years.[22] Based on a five-year cycle, inspection costs for a conventional system adds approximately $50 to annual O&M.

As conventional systems have no moving parts, repairs are often unneeded for the lifetime of a system. However, conventional systems sometimes need major repairs due to neglect (not pumping as needed), abuse (such as physical damage or parking cars on a drainfield), or misuse (such as putting too many solids, fats, or chemicals into the system). In one Florida study, holding tank repair had a mean cost of $4,579 and drainfield repair $3,181.[23] Another study from Florida estimated small drainfield repair cost at

---

[14] Amador, J. A., Görres, J. H., Loomis, G. W., & Lancellotti, B. V. (2018). Nitrogen loading from onsite wastewater treatment systems in the greater narragansett bay (rhode island, USA) watershed: Magnitude and reduction strategies. Water, Air, and Soil Pollution, 229(3), 1-13. https://doi.org/10.1007/s11270-018-3714-4
[15] Kozak, C. (2008). After 5 years of planning, Stumpy Point water plant to be built. The Virginian-Pilot.
[16] Olive, M., Daniel, L., & Donley, A. (2018). Septic Tank Survey: 2018. Institute for Social and Behavioral Science. https://stars.library.ucf.edu/isbs/9
[17] Diaz-Elsayed, N., Xu, X., Balaguer-Barbosa, M., & Zhang, Q. (2017). An evaluation of the sustainability of onsite wastewater treatment systems for nutrient management. Water Research (Oxford), 121, 186-196. https://doi.org/10.1016/j.watres.2017.05.005
[18] Vorhees, L., Harrison, J. (2021). Climate Change and Onsite Wastewater Treatment Systems in the Coastal Carolinas: Perspectives from Wastewater Managers. North Carolina Sea Grant. https://ncseagrant.ncsu.edu/wp-content/uploads/2021/09/Perspectives-from-OWTS-Managers-REPORT_Aug-24-2021.pdf
[19] Hoover, M., Konsler, T., Godfrey, J. (2016). Septic systems and their maintenance. NC State University Extension. https://content.ces.ncsu.edu/septic-systems-and-their-maintenance
[20] See Footnote 14
[21] See Footnote 16
[22] Riordan, M. J., DESIGN, L., & Jett, A. S. (2000). Septic system checkup: the Rhode Island handbook for inspection. Department of Environmental Management. http://www.dem.ri.gov/pubs/regs/regs/water/isdsbook.pdf
[23] See Footnote 16

$1,432.[24] As major repairs can be avoided with proper usage and routine inspections, we exclude these costs from our O&M estimates. That said, complete O&M costs for conventional systems has a national average cost of $152.[25] This can range up to $429 annually in Hawai'i.[26] This reinforces our estimate for annual pumping at $100. Adding in periodic inspections brings our estimated total annual O&M cost to $150.

Capital costs for a conventional system include site preparation and excavation, tank and piping, drainfield materials such as gravel or sand, and installation labor. We estimate total local costs from the following studies:

- Based on a study from Florida, the cost for a new system varies from $4,076 to $5,584.[27]
- A study of 73 recent projects in Hawai'i found that upgrading a cesspool to a conventional system has a mean cost of $15,692 with a high cost of $37,136.[28]
- A study from Hawai'i shows that mean upgrade cost varies from $13,933 for a one-bedroom house up to $17,436 for a five-bedroom house.[29]
- A survey of OWTS installers in North Carolina and South Carolina estimated hypothetical costs of four-bedroom and eight-bedroom house system. Four-bedroom houses had a capital cost range of $2,149 to $12,897 with an average estimate of $6,750; eight-bedroom houses had a capital cost range of $4,836 to $17,196 with an average estimate of $10,359.[30]
- A national study estimated capital costs for a new system at $3,580 to $8,885.[31]

Given a distribution of home sizes in Nags Head centered on three- and four-bedroom houses with a long tail to the right, we estimate conventional system cost at $7,500 with a likely range of $4,000 to $17,000.[32]

Advanced Systems

Advanced systems are increasing in popularity, though higher installation and operating costs so far inhibit widespread adoption. Unlike conventional systems, this class of system is eligible for National Pollutant Discharge Elimination System (NPDES) permits from the EPA and state water quality board.[33] These permits allow for point source discharge to a nearby waterbody, with periodic testing to ensure compliance with effluent concentration limits.

---

[24] Diaz-Elsayed, N., Xu, X., Balaguer-Barbosa, M., & Zhang, Q. (2017). An evaluation of the sustainability of onsite wastewater treatment systems for nutrient management. Water Research (Oxford), 121, 186-196. https://doi.org/10.1016/j.watres.2017.05.005
[25] Swann, C. (2001). The influence of septic systems at the watershed level. Watershed Protection Techniques, 3(4), 821.
[26] MacLeod, A. (2021). Development of a Method to Evaluate Decentralized Cluster Wastewater Systems as an Alternative for Cesspool Replacement (Doctoral dissertation, University of Hawai'i at Manoa).
[27] See Footnote 17
[28] See Footnote 26
[29] Wada, C. A., Burnett, K. M., Okuhata, B. K., Delevaux, J. M. S., Dulai, H., El-Kadi, A. I., Gibson, V., Smith, C., & Bremer, L. L. (2021). Identifying wastewater management tradeoffs: Costs, nearshore water quality, and implications for marine coastal ecosystems in kona, hawai'i. PloS One, 16(9), e0257125-e0257125. https://doi.org/10.1371/journal.pone.0257125
[30] See Footnote 18
[31] See Footnote 25
[32] Nags Head (2022). Town of nags head mapping and GIS. https://www.nagsheadnc.gov/310/Mapping-and-GIS
[33] NCDEQ (2022). NPDES program faqs. North Carolina Department of Environmental Quality. https://deq.nc.gov/about/divisions/water-resources/water-resources-permits/wastewater-branch/npdes-wastewater/faq

Advanced System: Individual Property

For individual properties, homeowners have a variety of technology choices. Here we outline a few options suitable for nitrogen reduction in coastal properties, with cost estimates available for initial capital and O&M. Excepting the denitrification mound system, the systems below have a conventional drainfield (included in capital cost). It is assumed that each property has land available for the drainfield and dispersal area, and in cases where a property cannot accommodate a drainfield, an NPDES permit is required with annual fees.

As these systems vary considerably in their complexity and energy usage, we retain the O&M costs given in each study to provide a more reasonable range of lifetime costs. For these systems, O&M includes required inspections with a licensed OWTS operator. Pumping costs and frequencies are comparable to conventional systems, and when not included in the original study, we add a $100 pumping fee to each system-specific O&M listed below.

Capital costs include site preparation and excavation, tank(s) and piping, electrical work, drainfield materials such as gravel or sand or woodchips, and installation labor. We estimate total local costs from the following studies:

Recirculating Sand Filter:
- A national study estimated system capital at $7,956 to $14,190, with $413 O&M.[34]

Activated Sludge or Aerobic Treatment Unit:
- A study in Florida estimated costs for a sludge reactor or a generic ATU at $10,920 capital; O&M for the sludge reactor is $622 and for the ATU is $752.[35]
- Eight recent ATU upgrade projects in Hawai'i had a mean capital cost $20,729 with a high of $42,887, and annual $1,289 O&M.[36]
- A study of ATU upgrades in Hawai'i found costs of $26,956 for a one-bedroom house, $29,856 for a three-bedroom, and $36,692 for a five-bedroom, with O&M of $752.[37]

Recirculating Media Filter:
- A proposal to install 75,000 systems in a Rhode Island watershed over fifteen years found the per system capital cost at $23,046 with $519 O&M.[38]

Denitrification Mound System:
- A Florida study found capital costs range from $15,099 to $18,098 depending on primary treatment fill, with $369 O&M and mound repair every 15 years at $4,141.[39]
- A feasibility study found maximum costs of $16,586 for a four-bedroom house.[40]

In a survey of OWTS professionals in North Carolina and South Carolina, recommendations for two hypothetical situations included aerobic treatment units, recirculating media filters, and denitrification

[34] See Footnote 25
[35] See Footnote 17
[36] See Footnote 26
[37] See Footnote 29
[38] See Footnote 14
[39] See Footnote 17
[40] Dowling, M. (2021) Guidance document for nitrogen reducing layered soil treatment area onsite wastewater treatment system. http://www.dem.ri.gov/programs/benviron/water/permits/isds/ialist/lstaman.pdf

mound systems.[41] Cost estimates were not broken down by system type. For a four-bedroom house, capital cost was estimated at $10,747 to $21,495, and O&M had an average estimate of $769; for an eight-bedroom house, capital cost was estimated at $8,598 to $64,487 with an average of $25,973, and O&M has an average estimate of $1,235. These estimates agree with the ranges provided in our other referenced studies.

Denitrification mound systems offer economic advantages but are novel enough that significant lifetime performance data doesn't yet exist.[42] Recirculating media filters and aerobic treatment units are reliable and popular for individual residences, and will be the main basis for our cost estimates.[43]

Given the above information, we estimate a cost of $22,000 for new systems with a likely range of $10,000 to $36,000. Estimated O&M is $700 annually with a likely range of $400 to $1,200.

Advanced System: Cluster or Package Plant

Similar to advanced systems for individual properties, there are multiple technologies available for communities and house clusters that pool their wastewater for treatment. Unlike with individual properties, cluster or package plant system costs are jointly determined by conveyance technology, treatment technology, land value, and the number of houses served. This greatly increases the complexity of estimating costs, but we will layout the different components to justify our estimates. As a final note, advanced systems have O&M costs for the residence unit (residential) and for the central treatment unit (central); combined, these costs form the household O&M cost.

Conveyance Technology

Due to the physical separation of residence and treatment plant, how the wastewater is conveyed to the treatment system impacts the technologies available and overall costs. There are three primary varieties of conveyance that differ at the residence level.[44] STEP systems use a holding tank at each residence to separate solids and fats, and then pump liquid effluent to a shared treatment plant. Houses with a grinder pump system blend all wastewater in a small buffer tank and then pump that solution via low pressure lines to the shared treatment plant; they save on tank pumping costs but typically have higher energy use and more involved maintenance. Gravity sewer systems are most common for municipalities, using buried pipes and lift stations to deliver wastewater to the shared treatment plant; due to hydraulic properties, the smaller the sewer pipe diameter, the steeper the slope required for natural flow. As gravity sewers are not often used with the small systems in our reference studies, and our study area is relatively flat, we will omit gravity sewers for this section and instead focus on STEP and grinder pump conveyance systems.

STEP Systems:

Based on an analysis of community projects by a STEP system vendor, the average household capital cost for a STEP system is $9,510 with a range of $6,610 to $15,570; this includes on-lot and service lines to

---

[41] See Footnote 18

[42] Gobler, C. J., Waugh, S., Asato, C., Clyde, P. M., Nyer, S. C., Graffam, M., Brownawell, B., Venkatesan, A. K., Goleski, J. A., Price, R. E., Mao, X., Russo, F. M., Heufelder, G., & Walker, H. W. (2021). Removing 80%–90% of nitrogen and organic contaminants with three distinct passive, lignocellulose-based on-site septic systems receiving municipal and residential wastewater. Ecological Engineering, 161, 106157. https://doi.org/10.1016/j.ecoleng.2021.106157

[43] See Footnote 14

[44] EPA (2002). Wastewater technology fact sheet sewers, pressure. https://www3.epa.gov/npdes/pubs/presewer.pdf

connect to the treatment plant.[45] In the study, the average connection size was 157 houses with a range of 25 to 409 houses. O&M costs are estimated from the following:

- A case study from Alabama for 65- and 132-house package plant systems with recirculating media filter found total O&M costs of $549. With pumping, the household cost is $649.[46]
- A case study from Texas of a 104-house system with recirculating media filter had O&M at $155 (central) and $96 (residential) per year, or $251 per year total.[47] With pumping, household cost is $351.
- A case study from Florida for a 1,500-house system connected to an existing WWTP found residential O&M costs at $190.[48] With pumping, full residential O&M cost is $290.
- A case study from New Zealand for a 250-house system with recirculating media filter package plant had combined O&M of $173.[49] With pumping, household O&M cost rises to $273.
- A vendor calculation of typical energy use and repair costs found residential O&M at $96.[50] With pumping, this cost rises to $196.

These studies allow us to estimate a $250 residential O&M for STEP systems, and $500 combined O&M for STEP systems paired to a recirculating media filter package plant. STEP systems can also be paired with activated sludge systems, and due to their higher energy use, combined O&M for activated sludge systems is approximately double the O&M for an equivalent sized recirculating media filter system.[51] This leads us to estimates of $1,000 household O&M for STEP systems paired to an activated sludge package plant. This fits in with expert estimates that a hypothetical 100-house system of various technology types would have combined household O&M of $599.[52]

For use in future analysis, we use the above residential O&M and household O&M costs to estimate that the central O&M cost for a recirculating media filter package plant is $250 and central O&M cost for an activated sludge or aerobic treatment unit package plant is $750.

Grinder Pump Systems:

Based on an analysis of community projects by a grinder pump vendor, the average household capital cost for a grinder pump system is $11,241 with a range of $6,440 to $15,570; this includes on-lot and service lines to connect to the treatment plant.[53] In the study, the average connection size was 221 houses with a range of 31 to 516 houses. O&M costs are estimated from the following:

[45] Orenco (2014). Small community collection systems construction costs. https://odl.orenco.com/documents/NFS-EFS-CC-1.pdf
[46] Orenco (2021). Case study Fulton Alabama. https://odl.orenco.com/documents/NCS-37.pdf
[47] Parten, S. (2019). Preferred Wastewater Systems for the Texas Hill Country and Over the Edwards Aquifer: Economic and Environmental Considerations. https://gato-docs.its.txstate.edu/jcr:7cd99555-9be7-43cf-9e41-d522245a4325
[48] Orenco (2021). Case study Vero Beach Florida. https://odl.orenco.com/documents/NCS-42.pdf
[49] Orenco (2021). Case study Piopio New Zealand. https://odl.orenco.com/documents/NCS-38.pdf
[50] Molatore, T. J. (2016). Operational Costs of Two Pressure Sewer Technologies: Effluent (STEP) Sewers and Grinder Sewers. https://odl.orenco.com/documents/NTP-STP-TJM-2.pdf
[51] See Footnote 26
[52] See Footnote 18
[53] See Footnote 45

- A vendor calculation of typical energy use and repair costs found residential O&M can range from $347 to $492.[54]
- A community in Missouri with grinder pumps had residential O&M costs of $556.[55]

These studies allow us to estimate a $450 residential O&M for grinder pump systems. To simplify further analysis, we will assume that the $200 household O&M difference between STEP ($250) and Grinder Pump ($450) systems holds for all treatment technology types or cluster sizes.

Central Treatment Plants and Dispersal Areas:

Once the wastewater is collected and conveyed to a central location, it must be treated and dispersed. Generally, this treatment system and drainfield is not on any homeowner's property, as it must be regularly accessed for inspections and maintenance. This poses a unique challenge in our study area, as Nags Head is well developed and there is a relative lack of open space. Using property lot maps and assessed land value data from the town, we searched for suitable vacant lots that did not abut estuary or coastal waters where they would be restricted due to setback requirements.[56] Vacant lots are primarily 0.15 to 0.3 acres in south Nags Head, with some larger lots in north Nags Head of 0.4 acres and larger; this likely limits the potential for cluster systems to 10-house systems in south Nags Head and 20-house systems in north Nags Head, barring property boundary or ownership changes. Based on assessed land values, an acre of vacant lot in south Nags Head averages $880,000 (n=4), while an acre of vacant lot in north Nags Head averages $441,000 (n=6). We will use these values to assess the additional household capital cost for land needed to house the system and drainfield.

In cases where a drainfield or compliant discharge location (i.e. surface or underground) is not available, an NPDES permit is required. These permits have strict requirements and depending on the waterbody being discharged to, can take months to years to acquire, if they are granted at all.[57]

Capital costs include treatment site purchase, site preparation and excavation at the household and central locations, household tank and electrical installation, conveyance line installation, drainfield materials such as gravel or sand, and installation labor. Costs are estimated from the following studies:

Activated Sludge or Aerobic Treatment Unit:
- A study evaluating 10-, 20-, and 100-house community systems in Hawai'i found household capital costs primarily depended on cluster size and whether the community used STEP or grinder systems.[58] For a 10-house system, technology costs range from $25,910 to $49,460 with STEP, and range from $34,330 to $63,060 with grinder; 0.25 – 0.6 acres has a likely cost of $18,000 to $37,000 with a maximum of $52,000. For a 20-house system, technology costs range from $22,140 to $42,400 with STEP, and range from $29,140 to $55,990 with grinder; 0.4 – 1.1 acres has a likely cost of $16,000 to $33,000 with a maximum of $48,000. For a 100-house system, technology costs range from $16,490 to $35,330 with STEP, and range from $24,430 to $48,460 with grinder; 1.3 – 4.2 acres has a likely cost of $12,000 to $24,000 with a maximum of $36,000.

---

[54] See Footnote 50
[55] Lee, G. M. (1997). low-pressure collection. Water Environment & Technology, 9(11), 33-34.
[56] See Footnote 32
[57] See Footnote 33
[58] See Footnote 26

Recirculating Media Filter:

- A 250-house system in Ohio had an average household capital cost of $17,651, including on-lot STEP system.[59] This system received an NPDES permit and does not use a drainfield.
- For a 65- and 132-house project in Alabama, average household capital cost was $39,082 for the smaller system and $29,001 for the larger system, both with STEP.[60] The smaller system would need 1.7 – 2.6 acres with a likely household cost of $14,000 to $29,000 and a maximum of $35,000; the larger system would need 3.1 – 4.6 acres with a likely household cost of $12,000 to $25,000 and a maximum of $30,000.
- A study evaluating 10-, 20-, and 100-house community systems with STEP found household capital costs primarily depended on cluster size.[61] For a 10-house system, technology costs range from $23,010 to $40,910; 0.35 – 0.75 acres has a likely cost of $24,000 to $48,000 with a maximum of $66,000. For a 20-house system, technology costs range from $23,480 to $42,400; 0.6 – 1.8 acres has a likely cost of $26,000 to $52,000 with a maximum of $79,000. For a 100-house system, technology costs range from $22,070 to $37,140; 2.1 – 7.9 acres has a likely cost of $22,000 to $44,000 with a maximum of $69,000.

Sequencing Batch Reactor:

- A study evaluating community systems found that a 10-house system would have likely household central technology capital costs of $4,270, a 20-house system would have likely capital costs of $3,420, and a 100-house system would have likely capital costs of $1,711.[62] Drainfield land costs are not included in this analysis but are assumed equivalent to other system types.
- A study from Germany evaluating the first generation of systems installed found average household central technology capital costs of $4,690 for systems smaller than 360 houses, and costs of $2,910 for systems handling between 600 and 800 houses.[63] This analysis is complicated by the fact that all but one of the systems use an effluent polishing pond, which is similar to a constructed wetland.[64] However, the polishing ponds are primarily an effluent storage buffer and are not strictly required if we assume an NPDES permit for direct discharge.

In a survey of OWTS professionals in North Carolina and South Carolina, recommendations for a hypothetical 100-house community system of varying technology types has an average household central capital cost estimate of $8,680 and a likely range of $2,950 to $16,110.[65] This requires 2 to 3 acres with a likely cost of $11,000 to $22,000 and a maximum of $26,000, for a likely total household cost of $25,180. Given the previously estimated costs for conveyance technology, these estimates for central capital and land requirements fit with our referenced studies.

O&M costs for central treatment systems are primarily for energy use and parts replacement. Activated sludge or aerobic treatment units, and sequencing batch reactors, involve more energy-intensive pumping of fluids and air, and thus have higher O&M costs. Our cost estimates for central O&M for a

---

[59] Orenco (2021). Case study Christiansburg ohio. https://odl.orenco.com/documents/NCS-41.pdf
[60] See Footnote 46
[61] See Footnote 26
[62] EPA (1999). Wastewater technology fact sheet sequencing batch reactors. https://www3.epa.gov/npdes/pubs/sbr_new.pdf
[63] HELMREICH, B., SCHREFF, D., & WILDERER, P. A. (2000). Full scale experiences with small sequencing batch reactor plants in bavaria. Paper presented at the , 41(1) 89-96. https://doi.org/10.2166/wst.2000.0016
[64] Cavalcanti, P. F., van Haandel, A., & Lettinga, G. (2001). Polishing ponds for post-treatment of digested sewage. part 1: Flow-through ponds. Water Science and Technology, 44(4), 237-245. https://doi.org/10.2166/wst.2001.0229
[65] See Footnote 18

recirculating media filter package plant was previously estimated at $250, and central O&M for an activated sludge or aerobic treatment unit package plant at $750. For sequencing batch reactors, one study found central O&M costs at $624 for small systems of the community size we are interested in.[66] Based on this, we will estimate central O&M at $625.

We omitted constructed wetland treatment systems from our analysis of cluster systems, though some communities might find these an appealing option. These artificial linear-flow ponds use plants and microbial action to consume nutrients, before dispersing treated water through a drainfield.[67] However, these systems are susceptible to overflow from storm surge or heavy rainfall, both of which are common occurrences in Nags Head.

Municipal Wastewater Treatment Plant

Municipal wastewater treatment plants (WWTP) are typically designed and built to handle an entire town or region's wastewater, and relevant capital costs include conveyance, the treatment plant, and land for the treatment plant. For the purposes of our calculations below, we will assume that the plant is built to handle 5,280 homes using 500 gallons per day. This is based off Nags Head current parcel count of 5,240 and a mean bedroom count in Nags Head of 3.98, which translates to a standard design capacity of 476 gallons per day per household.[68] An assumption here is that the community gets a NPDES permit for direct discharge into a regulated waterbody. An alternative solution is an ocean outfall, which pipes treated wastewater thousands of feet offshore and disperses it on the ocean floor; these are used in seaboard states including Massachusetts, New Jersey, Florida, and California.

Conveyance:

Gravity sewer systems are robust and can have low operating costs; one study[55] estimates O&M at $15 to $23.[69] Individual homes may have substantially higher residential O&M costs if their septic plumbing is below the nearest sewer line and they need a pump, but we will omit this case based on the fact that homes in our study area are typically elevated on stilts and assume $20 O&M.

Sewer lines are vast networks, typically connecting every home and business to the central treatment plant and relying on gravity as much as possible to carry wastewater downhill. This ideal topographic path often cuts across properties, and property rights and easement challenges often force path inefficiencies that raise capital costs; a study in Switzerland found that over 80% of the capital for centralized sewer treatment plants was spent on conveyance that mostly followed roads.[70] A study from a flat coastal city in India reached a similar conclusion on gravity sewers, where 84% of the capital required to build a centralized WWTP would be spent on conveyance.[71] One study from Portugal found that installation labor can vary from 40% to 70% of sewer capital costs, with variables including pipe depth, pipe diameter, pipe material, manhole depth, and number and power of pumping stations needed.[72] Based on this, we will

[66] See Footnote 62
[67] See Footnote 15
[68] See Footnote 32
[69] See Footnote 45
[70] Eggimann, S., Truffer, B., & Maurer, M. (2015). To connect or not to connect? modelling the optimal degree of centralisation for wastewater infrastructures. Water Research (Oxford), 84, 218-231. https://doi.org/10.1016/j.watres.2015.07.004
[71] Jung, Y. T., Narayanan, N. C., & Cheng, Y. (2018). Cost comparison of centralized and decentralized wastewater management systems using optimization model. Journal of Environmental Management, 213, 90-97. https://doi.org/10.1016/j.jenvman.2018.01.081
[72] Marchionni, V., Lopes, N., Mamouros, L., & Covas, D. (2014). Modelling sewer systems costs with multiple linear regression. Water Resources Management, 28(13), 4415-4431. https://doi.org/10.1007/s11269-014-0759-z

assume that 85% of project capital costs will be spent on gravity sewer conveyance, with a likely range of 75% to 90%.

Treatment Plant:

Analysis of 55 wastewater treatment plant projects in Israel revealed that the majority of systems used activated sludge technology, that capital costs were fairly consistent for any given treatment volume regardless of treatment technology, and that central O&M varied significantly depending on technology used and quality of final effluent produced.[73] Using the assumption of advanced secondary treatment for direct discharge into an environmentally sensitive waterbody, a plant in our study area would likely have a capital cost of $8.79m, or $1,664 per household; this could go as low as $8.03m, or $1,521 per household.

We use this treatment plant cost as the basis for gravity sewer capital costs. At our assumption of 85%, conveyance has an absolute cost of $49.79m, or $9,431 per household; evaluating the range of 75% to 90% gives us a likely absolute range of $35.2m to $87.9m, or $6,660 to $16,640 per household. As a point of reference, a vendor of STEP and grinder pump systems evaluated twenty community gravity sewer systems and found a national average cost of $19,704 per household, which in our study area would come to an absolute cost of $85.9m, or $16,270 per household.[74] This gives credence to our estimates and range.

As with package plants, a municipal wastewater treatment plant needs communal land for the central treatment unit. A comparable treatment plant in Wake County, North Carolina has a footprint of approximately 8 acres.[75] In our study area, this property size has a land capital range of $3.52m to $7.04m, or $670 to $1,330 per household. We also cautiously assume that public land (e.g. streets or drainage ditches) will be provided for sewer pipe paths at zero cost. Given our prior estimates, and an assumption of $1000 land capital per household, we reach a likely total household capital cost of $12,100.

An interactive dashboard shows median household sewer charges for 422 municipal sewer systems in North Carolina at $1,036 per year.[76] Given that the average household size in that dashboard is 2.5 persons, $1,050 is a safe assumption for central O&M, with a likely range of $840 to $1,260.

For comparison, we recall the residential costs assuming use of a grinder pump system at $11,241 capital and $450 O&M, and use of a STEP system at $9,510 capital and $250 O&M. We assume central O&M costs for the WWTP remains stable as there is no difference in wastewater quantities, and solids pumped from onsite holding tanks with STEP systems are usually delivered to the central wastewater plant for treatment anyways. As these two choices would overall be more expensive than the gravity system both for capital and O&M, we will omit them from our analysis.

---

[73] Friedler, E., & Pisanty, E. (2006). Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making. Water Research (Oxford), 40(20), 3751-3758. https://doi.org/10.1016/j.watres.2006.08.015
[74] See Footnote 45
[75] Raleigh (2022). Water & wastewater treatment plants. https://raleighnc.gov/water-and-sewer/water-wastewater-treatment-plants
[76] UNC (2022). NC water and wastewater rates dashboard. Environmental finance center. https://dashboards.efc.sog.unc.edu/nc

We next calculate total nitrogen abatement potential for each household over a 30-year lifetime. 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.[77] System types have ranges of effectiveness, and we will standardize effectiveness of each class of wastewater treatment system to a single estimate. When calculating marginal benefits, we consider "do nothing" as the baseline for abatement potential.

We reviewed the literature to determine effluent and reduction potentials for each system type in our study area. We exclude municipal WWTP from initial conditions, as there are no municipal wastewater treatment plants in Nags Head. We also assume that no household would change to an identical or less effective system type.

Table 2 shows the Total Nitrogen output expected from the Starting Point system type in the Baseline column with the abatement potential for the upgraded system in the columns to the right. Many of the highest reduction potential changes come from addressing cesspools and conventional systems with problematic drainfields. Upgrading properties with functional conventional systems achieves modest reductions in Total Nitrogen output, and there is minimal benefit to upgrading advanced systems.

Table 2 Total Nitrogen Effluent Totals and Abatement Potential, 30-Year Lifetime for Representative Household

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: Individual	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

[77] 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

A description of system types and considerations for each reduction potential and starting condition base outputs follows.

Conventional System – 40% TN Reduction, Influent to Effluent

These systems typically include a separation tank with a gravity-fed drainfield. The drainfield is often filled with native soils, sand, stone and gravel in an appropriate mixture and layering to encourage even distribution and bio-mat formation.[78] Underneath the drainfield, native soils and depth to water table are the primary local factors that influence efficacy.

- A modeling study calculated expected TN reduction for sandy soils at 7% (100% loading rate & 30 cm water table depth) to 31% (50% loading rate & 60 cm water table depth), for loamy soils at 11% to 59% TN reduction, and for clay soils at 29% to 80% TN reduction; this matches empirical studies showing 22% to 75% TN reduction in coastal soils.[79]
- A study measuring influent and effluent in Canadian and American OWTS on sandy/loamy soils found total inorganic nitrogen reduction averaging 34%, with little correlation between reduction and loading rates (seasonal or constant) or system age, and significant correlation between lower reduction and shallower water tables; of note, once nitrogen reaches the water table very little reduction happens.[80]

Given that Nags Head is predominantly sandy or loamy soil with high water tables, we estimate a 40% TN reduction.

Advanced System: Individual House – 75% TN Reduction, Influent to Effluent

These systems typically add a treatment unit inline between the separation tank and drainfield, and in some cases the additional treatment comes from a modified drainfield.[81]

Recirculating Sand Filter:
These systems pump wastewater through an enclosed sand box, providing enough percolation time for nutrient and BOD reduction before discharge to a typical drainfield.[82] They can achieve between 47% TN reduction and 60% TN reduction.[83]

Aerobic Treatment Unit:
These systems act like a miniature WWTP, pumping air into well-mixed wastewater to enhance bacterial decomposition. Newer high-efficiency units cycle the wastewater between aerobic and

---

[78] See Footnote 15
[79] D'Amato, V., Linker, L., Zhou, N., Wood, D., Ator, S., Brakebill, J., & Sekellick, A. (2016). Nutrient Attenuation in Chesapeake Bay Watershed Onsite Wastewater Treatment Systems—Final Report. 59. Tetra Tech, Tetra Tech.
[80] Robertson, W. D., Van Stempvoort, D. R., & Schiff, S. L. (2021). Nitrogen attenuation in septic system plumes. Ground Water, 59(3), 369-380. https://doi.org/10.1111/gwat.13065
[81] See Footnote 15
[82] See Footnote 15
[83] Oakley, S. M., Gold, A. J., & Oczkowski, A. J. (2010). Nitrogen control through decentralized wastewater treatment: Process performance and alternative management strategies. Ecological Engineering, 36(11), 1520-1531. https://doi.org/10.1016/j.ecoleng.2010.04.030. See Footnote 24

anaerobic conditions to enable denitrification. Typical ATUs achieve 19% to 55% TN reduction.[84] High-efficiency ATUs achieve 81% to 85% TN reduction.[85]

Recirculating Media Filter:
These systems are very similar to aerobic treatment units, with the addition of suspended membrane or cloth "filter" media in the wastewater tank that give beneficial bacteria and algae surfaces to grow.[86] These can achieve 62% to 83% TN reduction when faced with variable influent loading.[87] Most systems achieved between 75% and 78% TN reduction, with low outliers and poorer performance for seasonally occupied houses.[88]

Denitrification Mound System:
These systems use a constructed drainfield made of layered sand and woodchips to provide optimal conditions for denitrification. They can achieve 95% to 97% TN reduction under variable loading conditions in a dry climate.[89] Another study found 83% to 94% TN reduction in a wet climate, with reduced performance noted during the cold winter.[90]

Given the popularity of aerobic treatment units and recirculating media filters, we will estimate a middle ground of 75% TN reduction for these advanced systems.

Advanced System: Cluster or Package Plant – 80% TN Reduction, Influent to Effluent

These systems separate solids at the residence and then pump liquid or slurry influent for bulk treatment at a central system, and generally use a large drainfield to handle final dispersal of effluent.[91] They occasionally have full time employees to monitor their function, but in most cases run on their own.

- A study in a tourism-heavy coastal community found 74% average TN reduction, with seasonal variation from 55% reduction in winter during low loading, up to 87% reduction in summer when loading was highest.[92]
- A companion study evaluated TN reductions by system type and found seasonal variations for Extended Aeration (90% summer, 75% winter), Advanced Media Filtration (84% summer, 76% winter), and Sequencing Batch Reactor (83% summer, 75% winter); much of the variation was attributed to loading rates and temperature differences.[93]

---

[84] Babcock R, Barnes MD, Fung A, Goodell W, Oleson KLL. (2019). Investigation of Cesspool Upgrade Alternatives in Upcountry Maui Final Report. Prepared for the Hawaii Department of Health, Safe Drinking Water Branch. https://health.hawaii.gov/sdwb/files/2020/04/CesspoolUpgradeAlternativesUpcountryMaui.20191018_FinalReport.pdf.
[85] Babcock, J., Roger W, Senthill, A., Lamichhane, K. M., Agsalda, J., & Lindbo, G. D. (2015). Enhanced nitrogen removal with an onsite aerobic cyclic biological treatment unit. Water Science and Technology, 71(12), 1831-1837. https://doi.org/10.2166/wst.2015.172
[86] EPA (2000). Wastewater technology fact sheet trickling filters. https://www3.epa.gov/npdes/pubs/trickling_filter.pdf
[87] See Footnote 83
[88] Ross, B. N., Hoyt, K. P., Loomis, G. W., & Amador, J. A. (2020). Effectiveness of advanced nitrogen-removal onsite wastewater treatment systems in a new england coastal community. Water, Air, and Soil Pollution, 231(11)https://doi.org/10.1007/s11270-020-04911-5
[89] See Footnote 83
[90] See Footnote 42
[91] See Footnote 15
[92] Mahoney, R. N. (2016). Nutrient and Bacteria Dynamics of Package Treatment Plants in Coastal Carteret County, North Carolina.
[93] O'Driscoll, M., Bean, E., Mahoney, R. N., & Humphrey, C. P. (2019). Coastal tourism and its influence on wastewater nitrogen loading: A barrier island case study. Environmental Management (New York), 64(4), 436-455. https://doi.org/10.1007/s00267-019-01201-7

- A study from Germany evaluating sequencing batch reactors serving small (<360 houses at 2.5 people each) and medium (600 – 800 houses at 2.5 people each) rural communities found 84.8% average TN reduction for small and 89.0% average TN reduction for medium communities.[94]

Controlling nitrogen in summer is more critical due to the higher dangers of eutrophication from elevated sunlight and warmer water.[95] Therefore, we will give additional weight to summer reduction numbers and therefore use 80% TN reduction as our estimate.

We omitted constructed wetlands from our study area, though other communities may find them worth pursuing. In traditional format, constructed wetlands can be moderately effective and achieve 40% to 50% TN reduction.[96] With an aeration tower to increase aerobic conditions (and O&M costs), these systems can achieve greater than 80% TN reduction and anecdotally were found to be aesthetically pleasing to community residents.[97]

Municipal Wastewater Treatment Plant – 90% TN Reduction, Influent to Effluent

These systems generally handle full wastewater flow from residences and businesses, separating solids and liquids for differing treatment and disposal. Liquid effluent generally flows to a river, lake, or bay and is closely monitored for effluent nutrient and microbe concentrations according to its permit.[98]

- A study of 15 municipal sewer systems found 81% to 97% TN reduction, with the caveat that every system met discharge standards with a relatively stable absolute effluent level of 1.6 – 5.3 mg/L TN.[99] The study notes that centralized plants have controls and operator oversight to continuously adjust processes to influent concentrations, so that less is done if influent TN load is lower than normal, and more is done if influent TN load is higher than normal.
- The previously referenced wastewater treatment plant in Wake County has a permit that allows maximum TN load and discharge on an annual basis of 3 mg/L.[100] As a point of reference, average influent TN load at ten package plants in Germany was 63.5 mg/L.[101] This allowable effluent limit represents an average requirement for 95% TN reduction.

Based on this, 90% TN reduction is our estimate.

Starting Conditions Not Yet Covered

To evaluate reduction, we need baseline effluent concentrations for low quality systems. For straight pipe discharges, and for cesspools where the holding tank is in direct contact with the groundwater table or is in sandy soil where channeling is likely (which represents all of our study area), we assume that no treatment occurs before effluent reaches groundwater (0% TN reduction). We exclude greywater systems as they are uncommon in our study area, though they can also be assumed to provide no treatment.

---

[94] See Footnote 63
[95] Paerl, H. W., Hall, N. S., Peierls, B. L., & Rossignol, K. L. (2014). Evolving paradigms and challenges in estuarine and coastal eutrophication dynamics in a culturally and climatically stressed world. Estuaries and Coasts, 37(2), 243-258. https://doi.org/10.1007/s12237-014-9773-x
[96] Lee, C., Fletcher, T. D., & Sun, G. (2009). Nitrogen removal in constructed wetland systems. Engineering in Life Sciences, 9(1), 11-22. https://doi.org/10.1002/elsc.200800049
[97] Ye, F., & Li, Y. (2009). Enhancement of nitrogen removal in towery hybrid constructed wetland to treat domestic wastewater for small rural communities. Ecological Engineering, 35(7), 1043-1050. https://doi.org/10.1016/j.ecoleng.2009.03.009
[98] See Footnote 33
[99] See Footnote 83
[100] NCDEQ (2022). Little Creek WRF Permit. https://deq.nc.gov/news/events/little-creek-wrf-pemit-nc0025453
[101] See Footnote 63

Many properties in Nags Head are within a few feet of sea level and shallow groundwater and sandy soils are prevalent, and these conditions do not meet the required unsaturated soil depth for a typical conventional system drainfield.[102] We assume that conventional systems with problematic drainfields are representative, and these provide approximately 20% TN reduction.[103] Of note, sea level rise is likely to reduce unsaturated soil depths and therefore reduce the efficacy of problematic drainfields or lead to complete drainfield failure; sea level rise can also mean currently functional drainfields will become problematic in the near future.

Functional existing systems, either conventional or advanced, are assumed to have equivalent TN reduction as new systems.

Step 4: Standardize Cost Estimates

Step 4: Standardize data for marginal abatement cost, e.g. dollars per one unit of pollution prevented.

We standardize the data from Step 3 to calculate marginal 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 marginal abatement costs based on the lifetime cost ranges we derived in Step 3. The results are below in Table 3.

Table 3 Marginal Abatement Costs ($/kg-N) for a Representative Household Over 30-Year Lifetime, with (low-high) MAC Range

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)

[102] 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
[103] See Footnote 79

In absolute terms, the lowest marginal abatement cost is $57.35 for transitioning a cesspool to a conventional system. Across all potential solutions shown, the average marginal abatement cost for upgrading a cesspool is $128.67/kg-N, for problematic conventional systems the average MAC is $176.96/kg-N, and for functional conventional systems the average MAC is $281.08/kg-N. This shows clear benefits to addressing cesspools and problematic conventional systems, regardless of end point. Depending on the solution chosen, upgrading functional conventional systems can be cost effective.

Alternatively, the most expensive solutions come from upgrading advanced systems due to high cost and limited reduction potential. Due to the outsized influence of land costs in our study area, marginal abatement costs for small cluster systems are relatively high. In areas where land is less expensive, and larger lots are available, the marginal abatement cost distribution would likely look very different. We also recognize that conventional systems may not be an appropriate upgrade end point for properties at risk of high groundwater table or frequent flooding due to sea level rise and climate change.

Step 5: Plot Results

Step 5: Plot the cost against the amount of abatement for each technique.

In Figure 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 marginal abatement cost (y-axis) for each end point. Error bars show the likely range for each marginal abatement cost to highlight to the reader that for any given project, it is worth pursuing all options that could be within budget to achieve the nitrogen reduction target. 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; a deeper analysis shows that this is primarily due 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.

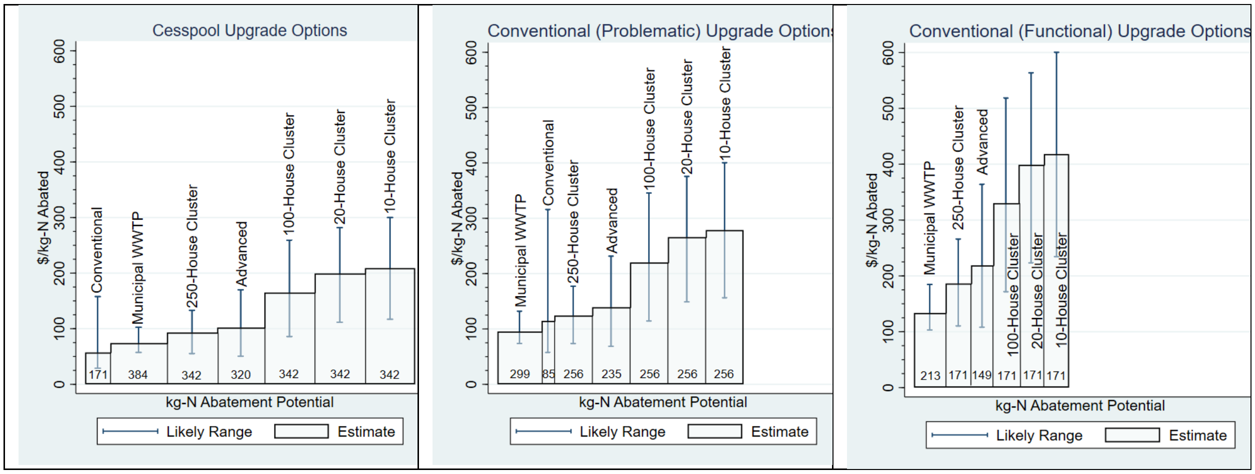

Figure 1 Abatement costs for three starting points. The bar width represents proportional abatement potential, and the inset number indicates the absolute kg-N abatement potential for that particular upgrade option, given a starting condition. For example, in the leftmost figure (Cesspool Upgrade Options), we can see that adopting a Conventional system would provide 171 kg-N abatement (from Table 2) at a marginal cost of $57.35/kg-N (from Table 3); the error bars indicate that depending on the particular house site and project requirements, a realistic marginal abatement cost range is $28/kg-N to $157/kg-N.

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 town agrees to fund investment in upgrades through one of its grant programs, but there is debate over what to fund. In particular, town managers must balance reducing water in this neighborhood with other water quality improvement projects they can fund.

One manager suggests putting in a 20-house cluster system. Looking at the marginal abatement costs for the cesspool homes: 10 houses each abate 11.4 kg-N annually at a marginal cost of $199/kg-N; 5 houses have problematic conventional systems and each abate 8.5 kg-N annually at a marginal cost of $266/kg-N; 5 houses with operational conventional systems each abate 5.7 kg-N at a marginal 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 also provides the town with the opportunity to invest in alternative abatement approaches at a much lower cost. The 20-house cluster system generates 15 kg-N additional annual abatement, relative to the second manager's plan, but the town is paying $399 per kg-N removed for the last unit of abatement. This money could be better spent on other upgrade investments; for instance, upgrading additional homes with cesspools to advanced systems in other neighborhoods would yield four times the N abatement per dollar spent.

A study consistent with this example found that cost-effectiveness depends on how close neighbors are, how steep and rugged the terrain is, and whether the ideal topographic path for sewer lines follows public land or streets. For one example valley community, the study found that the benefit-cost ratio peaked when 76% of houses were connected to a large cluster system and the more remote houses used individual or small cluster systems.[104] This ratio may not line up exactly with Nags Head or other coastal communities, but it does reinforce the idea that a one-size-fits-all solution is likely not the most cost-effective means to improving environmental and groundwater pollution.

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 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).[105] 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%.[106]
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 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.[107] Informal reminders of septic capacity to all homeowners and notices in rental properties for renters can reiterate that water use should be limited.
3. High tides or a storm surge can raise groundwater tables with very little warning, causing at-risk drainfields to mix with groundwater.[108] Extreme precipitation can increase transport and lead to higher absolute values of nutrients and increased ammonium concentrations reaching the

---

[104] See Footnote 70
[105] See Footnote 102
[106] 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
[107] Airbnb Nags Head Vacation rentals. (2022, February 12). https://www.airbnb.com/nags-head-nc/stays
[108] 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

environment.[109] 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%, and shorten maintenance intervals due to increased sludge accumulation.[110] Communities can educate and incentivize homeowners to remove their garbage disposals or dispose of most food scraps in garbage or compost bins.

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 have the desired pollution reduction effects. 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.[111] 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 sq.ft. lawn can produce ~5.44 kg-N/year.[112] 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.[113] These require regular maintenance if subject to sedimentation.

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.

---

[109] 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. See Footnote 76

[110] 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

[111] 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

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

[113] 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

    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 changes in 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.[114]
5. Continue to monitor groundwater and surface water quality for the lifetime of all projects; adjust implementation plan as needed.
    a. Reevaluate the marginal abatement cost distributions and abatement potentials as new OWTS technologies become practicable, as costs change, or as regulations are updated.

The journey of a thousand miles begins with one step. While the workplan 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.

[114] 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.