Assess Vulnerability of OSTDS to SLR and Storm Surge to Develop Adaptation Plans Phase 1

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EXECUTIVE SUMMARY

The purpose of this study is to assess the vulnerability of onsite treatment and disposal systems (aka OSTDS, septic systems) to three potential sea level rise scenarios and potential storm surge. This was done through the development of a new multi-criteria weighted vulnerability assessment method. Additionally, this project used ArcNLET GIS modeling to estimate nitrogen exports from residential septic systems to nearby waterbodies. Also as part of this project was the research and synthesis of a wastewater technologies report containing information about the range of technologies available, cost examples and funding opportunities. This project also presented findings through several public presentations and project details have been made publicly available through a freely accessible website. All data used for this project were derived from publicly available sources (see Table 4.1) and were transformed using ArcGIS 10.6.1 and Microsoft Excel 365. Transformed data were used to identify residential septic systems in the study area, calculate vulnerability assessment scores for identified systems and estimate nitrate (NO_3) exports to area waterbodies. Vulnerability assessment scores were also used in ArcGIS Hot Spot Analysis (Getis-Ord Gi*) to identify hot and cold spots of the spatial distribution of individual scores. Additional information was derived by calculating the average of individual scores by subdivision, identifying the number of septic systems in each subdivision and calculating the density of septic systems per acre for each subdivision. ArcNLET modeling was also used on multiple subsets of the main septic system source location data such as all septic systems subject to 1-food, 2-foot and 3-foot of sea level rise.

Results of this study identified 2,938 residential septic systems in the study area. Vulnerability assessment scores ranged from 30 – 460. High scores, indicating more vulnerability, were found primarily in the north of the study area around Stokes Creek, and the northern extent of San Sebastian River. Low scores, indicating less vulnerability, were found primarily in the southern portion of the study area around West Augustine and Salt Run. ArcNLET modeling estimates show that the highest nitrate loading of these septic systems is to Salt Run with 1,291 lbs/yr. The second highest loading was to Stokes Creek with 593 lbs/yr. Using the vulnerability assessment and nitrate modeling estimates together can indicate where areas should be prioritized for projects that can reduce the vulnerability of septic systems and loading to waterbodies. Areas that have high vulnerability assessment scores and are estimated to be contributing nitrogen to waterbodies should be addressed soonest. In this study, septic systems in Stokes Creek have high vulnerability and are estimated to contribute nitrate-nitrogen for area waterbodies. Areas such as Stokes Creek should be prioritized for projects that can reduce the vulnerability of the septic systems and reduce the nitrogen loading. Further research should be done to validate the results of these calculations and estimates such as monitoring ground and surface water nitrogen levels to calibrate ArcNLET modeling and monitoring groundwater elevation and verifying storm surge events to validate vulnerability assessment parameters.

1. INTRODUCTION

Wastewater infrastructure in low lying coastal communities face multiple threats such as sea level rise, storm surge, increased flooding and precipitation, and rising groundwater levels. Yet often efforts to identify a community's vulnerabilities to these same threats focus on the more visible, above ground structures and infrastructure (Cox, Dowling, et al. 2020). Some work has been completed to identify risks and impacts to municipal sanitary sewer systems as these are major infrastructure elements typically maintained by municipalities. But climate related threats to onsite treatment and disposal systems (OSTDS; commonly referred to as septic systems) has only recently become the subject of more research (Cox, Surabian, et al. 2020; Cox, Dowling, et al. 2020; Cox, Loomis, and Amador 2019; Cooper, Loomis, and Amador 2016; Mihaly 2018; Flood and Cahoon 2011; Azevedo de Almeida and Mostafavi 2016). While it is recognized that they face many of the same risks as other infrastructure – rising sea and groundwater levels, and increased inundation frequency from flooding – septic systems are privately owned and therefore fall to the property owner to deal with. This means that property owners must be educated about what the risks are, how to assess them, and understand what the consequences are should those risks become reality. This is not a level of education most homeowners are likely to have. Additionally, while one homeowner may be knowledgeable of the risks it would also have to be assumed that they have the financial resources to change the situation. If the change needed is to connect to municipal sewer infrastructure and the homeowner is not near existing infrastructure this might be simply infeasible to achieve. It would also not achieve significant change for a single homeowner to abandon their septic system for connection to the sewer system when there are still other septic systems remaining in the area that are still at risk and exporting to nearby waterbodies. The level of change needed to reduce vulnerability and exports would need to be at the subdivision or community level. These types of projects are usually done by the local municipality or wastewater authority and often involve many years of planning and pursuit of funding opportunities to achieve such a project.

The methods available through this project can be used by those municipalities or wastewater authorities to recognize which septic system are at risk of climate change related impacts and are exporting to nearby waterbodies and can prioritize those with the greatest risk and exports for conversion to a municipal wastewater treatment system. Additionally, the data resulting from this project can be used to support funding applications for such projects as well as used in public education programs about the risks community septic systems are facing from climate change related impacts and the current nitrogen exports from these systems.

1.1. Septic Systems

Conventional septic systems operate by allowing solids to settle to the bottom of the tank, while letting liquids skim out to seep through a drainfield into below ground soils. The elements in the wastewater that enter the tank include organics, nitrogen, phosphorous, pathogens and chemicals/pharmaceuticals. The most common potential pollutants from onsite wastewater treatment systems include nitrogen, phosphorous (Humphrey et al. 2014; Lapointe et al. 2015; Lusk et al. 2017; Lusk 2018b; Paerl 2014), pathogens (Lapointe, Herren, and Bedford 2012; Lapointe, Herren, and Paule 2017; Reay 2004; Schneeberger et al. 2015), pharmaceuticals and personal care products (Del Rosario et al. 2014; Yang et al. 2016) although nitrogen pollution may be the most well-recognized output of poorly functioning septic systems. It is important to note that nitrogen and phosphorous (and to some extent FIB and some of the ingredients in pharmaceuticals and personal care products) are naturally occurring elements in nature and only become 'pollutants' when they reach harmful levels of concentration. Nitrogen is the export that gets the most attention usually because it is often the limiting nutrient to eutrophication and harmful algal blooms in surface waters (Humphrey, O'Driscoll, and Zarate 2010; Humphrey et al. 2013; Humphrey Jr. et al. 2012; Lapointe, Herren, and Bedford 2012; Lusk et al. 2017; O'Driscoll et al. 2019; Withers et al. 2014) although phosphorus can be a limiting nutrient as well (Guildford and Hecky 2000). 'Nitrogen' is used in the general, there are actually several species of nitrogen involved in the waste processing cycle of

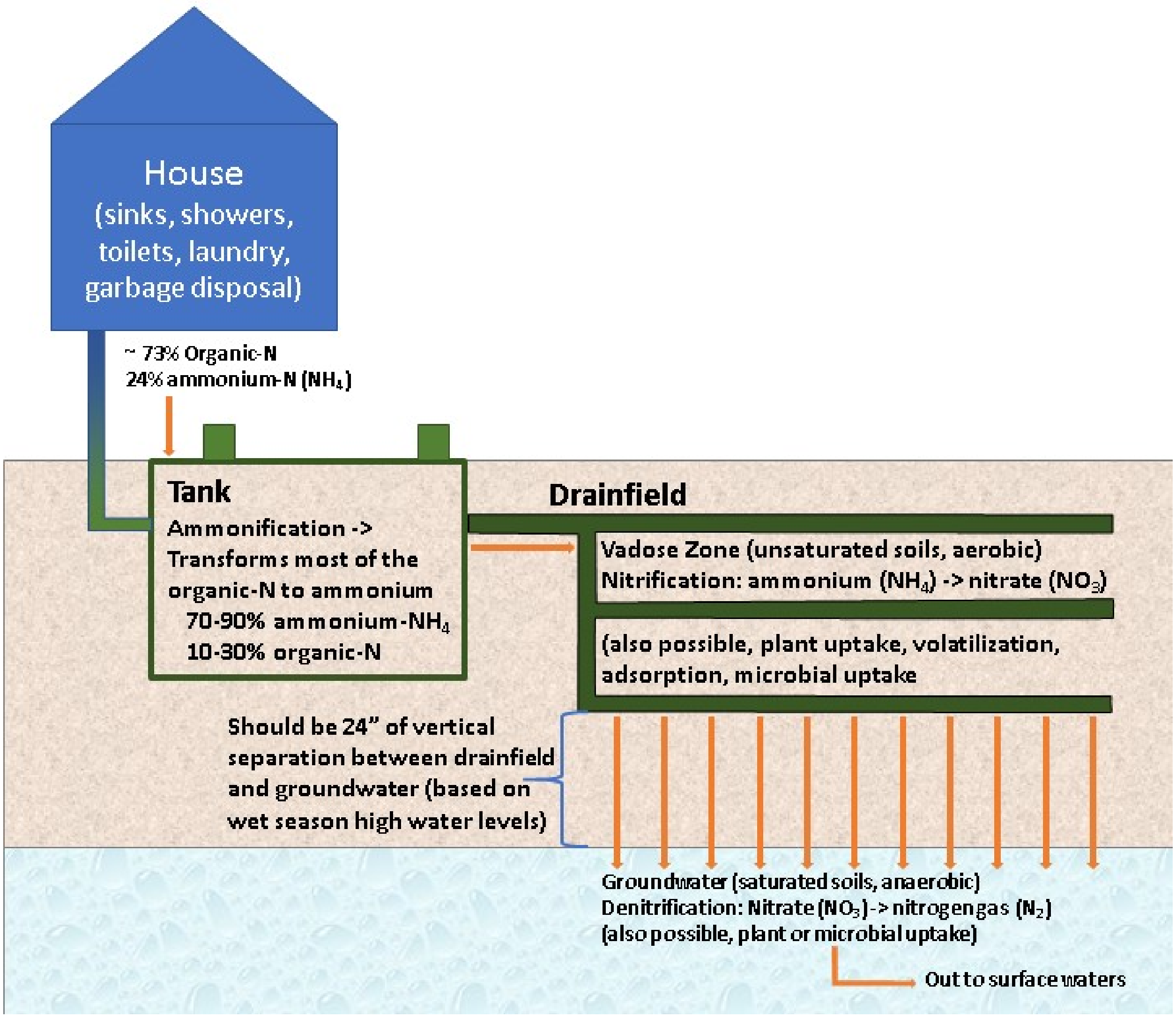

Figure 1.1 The nitrogen cycle in a conventional septic system. Nitrogen in the form of organic N and ammonium N (NH_4) move from the house to the septic tank. Inside the tank most of the organic N will convert to ammonium N. In the vadose zone below the drainfield the nitrification process converts ammonium to nitrates (NO_3) if there is enough vertical separation distance between the drainfield and the groundwater. In the anaerobic zone of the groundwater, denitrification converts nitrate to nitrogen gas (N_2).

septic systems including nitrates (NO_3), nitrites (NO_2), ammonia (NH_3) and ammonium (NH_4). FIB, also used as a general term, includes fecal coliform bacteria (e coli) and entero viruses (enterococci) which will be discussed below.

Valiela estimated that each person in a household releases 4.8kg of nitrogen per year (Valiela et al. 1997) and Lusk et al estimate 8.7 g/person/day or 3.12 kg/person/year (Lusk et al. 2017). The process of converting nitrogen outputs to nitrogen gas in septic systems takes many steps (see Figure 1.1). Wastewater leaving the house contains nitrogen with approximately 74% organic nitrogen and approximately 24% ammonium (NH_4). While in the tank, organic nitrogen will convert via ammonification to ammonium (NH_4). Effluent leaving the tank to enter the drainfield will then be approximately 70-90% ammonium (NH_4) and 10-30% organic nitrogen (Gurpal S. Toor 2019). Once the ammonium enters the drainfield it will most likely be converted to nitrate (NO3) via denitrification in the unsaturated soils (aka vadose zone). It may also be taken up by plants if the root zone is within the drainfield, or it may be converted to ammonia gas (NH_3) through volatilization (when the pH in the soil is greater than 8). If there are any negatively charged particles in the soil, the ammonium maybe adsorbed to these. Ammonium may also be used by microorganisms for food (Lusk et al. 2017; Valiela et al. 1997). After passing through the soils, nitrates will enter the groundwater. In this anaerobic zone denitrification will convert nitrates (NO_3) to nitrogen gas (N_2). Nitrates may also be taken up by plants or microbes in groundwater. If ammonium and nitrates are not fully processed through nitrification/denitrification they are likely to move into surface waters where even a small amount (1 mg/L) can lead to harmful algae outbreaks.

When the full process does not happen, elevated levels of ammonium and/or nitrates enter aquifers, drinking water wells and surface waters. For the full process to happen there must be an adequate amount of organic matter in the unsaturated soils (aka the vadose zone) below the drainfield and sufficient distance between the drainfield and the groundwater table (Valiela et al. 1997) (see Figure 1.1 again). There should be 24" between the drainfield and the high groundwater table (determined by the wet season high level) and the soils should contain organic matter capable of completing the nitrification process.

While this is not true for all coastal communities, many are at or near sea level and have a predominance of inorganic sandy soils. For these communities, there is high likelihood for incomplete nitrogen conversions. When these conditions are compounded by sea level rise (see section 1.4), increased flooding and precipitation (see section 1.6), storm surge (see section 1.7), and/or rising groundwater levels (see section 1.8), there is an increasing opportunity for incomplete nitrification and/or denitrification, enabling ammonium and/or nitrates to enter surface waters. When there is a lack of sufficient distance and/or organic matter between drainfields and groundwater elevated levels of nitrogen (in the form of ammonium and/or nitrates) could enter groundwater resources and transport to drinking water wells, aquifers, or surface water bodies. When high levels of nitrogen (>10 mg/L) enter private drinking water wells, the potential health risks to humans can include decreased oxygen in the blood, blue baby syndrome or even cancer (Oosting and Joy 2011; Ye 2019). When high levels of nitrates (>1 mg/L is an adequate food source for algae to grow) enter surface waters it can contribute to harmful algae blooms, reduced oxygen in the water, eutrophication, reduced biodiversity and ecosystem health (Cole et al. 2006; De 2015; Wang et al. 2013; Withers et al. 2014). When algae consume the nitrates and grow to such an extent that they block sunlight from reaching submerged aquatic vegetation (SAV), causing the vegetation to die which can deprive fish of a necessary food source. When the algae have consumed all the nitrogen they begin to die and through decomposition reduce the supply of oxygen in the water which can lead to fish kills. Some algae also produce toxins that can directly cause fish kills as well as skin rashes if humans come in contact with it (SJRWMD 2021).

In addition to nitrogen, phosphorous, pharmaceuticals and pathogens may also transport out of systems with the effluent (Lapointe, Herren, and Paule 2017). Kramer et al estimate phosphorus exports per person per year at 1.2 kg/person/year (Kramer et al. 2006) and Lusk et al estimate 1.6 g/person/day or 0.584 kg/person/year (Lusk et al. 2017) and while most of this is exported in septic system effluent phosphorous readily binds to soils (Lusk et al. 2017) and so does not usually pose a human health threat. This sounds good except that it only takes very small amounts, 0.03mg/L, of P to lead to eutrophication in surface waters where P is the limiting source (Charles P. Humphrey et al. 2014; Iverson et al. 2018; Lusk et al. 2017).

'Pathogens,' is the more appropriate term for pollutants that originate in fecal material although not all are disease causing. These include the previously mentioned fecal coliform bacteria and enteric viruses such as enterococcus. Lusk et al estimates fecal coliform bacteria at 10^6-10^9 per gram of human feces and enteroviruses at 10^3-10^7 (Lusk et al. 2017). The wide variety of fecal contaminants would require specific tests for each one, making this level of testing impractical. Instead, FIB is used to indicate the likely presence of pathogens. Pathogens in groundwater can contaminate private drinking water wells and surface waters (Schneeberger et al. 2015; Weiskel, Howes, and Heufelder 1996) where there is not sufficient distance in the unsaturated zone beneath drainfields (Lusk et al. 2017). Lusk et al notes that counts for pathogenic bacteria in septic tank effluent can be as high as 10^5-10^8/100ml for *e coli* and 10^3-10^4/100ml for enteroviruses. When this is compared to the amount required for infection doses, just 10 organisms for some e coli species and 10^6-10^7 for others, and only 1 organism for enterovirus, we can see how significant the human health risk is from these contaminants (Lusk et al. 2017).

Recent research is also showing that pharmaceuticals and personal care products are another export of septic systems (Del Rosario et al. 2014; Lusk et al. 2017) referred to as 'TOrCs' or trace organic chemicals. A growing body of literature is revealing the danger these pose to the environment and marine life in surface waters (Santos et al. 2013; Snyder et al. 2003). For example, hormones in pharmaceuticals can lead to physical and behavioral changes in male fish (feminization) that impact diversity and reproduction (Vajda et al. 2008).

1.2.Vulnerability of Septic Systems to Climate Change

The IPCC and the Fourth National Climate Assessment have both indicated that as the planet warms we will experience rising sea levels, more rainfall per year and more intense storms (IPCC 2014; Carter, L., et al. 2018). These events present several different aspects of threats to onsite wastewater treatment systems from sea level rise, storm surge, increased flooding and precipitation, and rising groundwater levels (Cox, Surabian, et al. 2020; Cox, Dowling, et al. 2020; Cox, Loomis, and Amador 2019; Cooper, Loomis, and Amador 2016). Extreme and/or sustained exposure to these elements could lead to saturated soils that prevent septic systems from functioning properly, complete inundation – where tanks, drainfields or both are completely underwater -, or could even elevate septic systems out of the ground, any of which could release untreated sewage into the environment creating a significant public health and environmental hazard (Cooper, Loomis, and Amador 2016; Cox, Dowling, et al. 2020).

1.3.Vulnerability of Septic Systems to Sea Level Rise

As glaciers melt due to rising temperatures, their solid mass is converted to liquid and deposited into oceans, contributing to sea levels rise. Also, as water molecules warm, they increase in size, causing the oceans to expand. For properties that are on the coast, rising seas may simply overtop the property, causing inundation of wastewater treatment systems which may not at first be perceptible as the systems are underground.

Additionally, saltwater can intrude to groundwater from the side and is heavier than fresh water thus pushing the fresh groundwater up (Azevedo de Almeida and Mostafavi 2016), and reducing the vertical separation distance between drainfields and groundwater levels (Cox, Loomis, and Amador 2019). When the vertical separation distance is reduced, the biological process of nitrogen conversion does not have the requisite time to move through enough soil gradient to complete the conversion process into an inert nitrogen gas. In low lying coastal communities these consequences can be further exacerbated by already elevated groundwater tables, further decreasing the distance between infrastructure and increasingly saline groundwater. It has been noted that coastal communities are likely to experience more of the effects of sea level rise than other locations, possibly by as much as 1m more than other communities (Flood and Cahoon 2011) which could make coastal septic systems more vulnerable than inland septic systems.

1.4.Aggregating Sea Level Rise and High Tide Flooding

As sea levels rise, high tides, especially King tides, will also reach higher onto the land surface. The East and Gulf coasts of the U.S. have been identified as some of the areas likely to be most impacted by these events (Dahl, Fitzpatrick, and Spanger-Siegfried 2017; Kruel 2016; Spanger-Siegfried, Fitzpatrick, and Dahl 2014). This increases the potential for septic systems to be overtopped by rising sea levels because the average high tides will thus be higher and more frequent than previously. It can already be seen that sea level rise is leading to increased depth and duration of tidal flooding in both the East and Gulf coasts (Spanger-Siegfried, Fitzpatrick, and Dahl 2014). Dahl et al estimate that flood frequency at the Mayport station in northeast Florida will increase from 6.4 events per year to 27.4 events per year by 2030 and to 100.9 events per year by 2045. The increase in flood events increases the risk that coastal septic systems face from inundation due to sea level rise and increased high tide flooding.

1.5.Vulnerability of Septic Systems to Increased Flooding and Precipitation

In addition to SLR, climate change is increasing storm event frequency and storm intensities (Flood and Cahoon 2011). These weather events have the potential to overwhelm systems with increased stormwater and wind driven rains that push waters over land. Where OSTDS are in sandy soils and adjacent to water bodies, rainfall events and changes in the groundwater table can increase the amount of nutrients exported from these systems (O'Driscoll et al, 2014). For example, Lapointe et al. (Lapointe, Herren, and Bedford 2012) demonstrated that the St. Lucie Estuary experienced increased levels of nitrogen, phosphorous and fecal indicator bacteria following high rainfall events.

Short term consequences from increased precipitation includes greater volumes of runoff. When runoff happens over septic tanks and drainfields it can temporarily increase groundwater levels that may either prevent the biological processes of nitrogen conversion from happening or can inundate the system, causing effluent to back up into the system or home (Flood and Cahoon 2011).

When increased precipitation happens frequently, as is being seen with the increases in storm frequencies and intensities, the consequences may no longer be short term because the groundwater levels may not have the opportunity to recede to previously normal levels. This would lead to a system failure because of inundation.

1.6. Vulnerability of Septic Systems to Storm Surge

As sea levels rise and storm frequency and intensities are increasing, storm surge is also becoming a greater threat to coastal communities (Neumann et al. 2015). Indeed, Neumann et al note that much of the more than $50 billion in damages from Hurricane Sandy were attributed to storm surge. Coastal communities face greater flooding events during extreme weather because of the combined effects of wind, waves, tides and storm surge (Vitousek et al. 2017). Just as with the increased volumes of runoff from increased flooding and precipitation, storm surge can also saturate coastal properties that may be serviced by septic systems. Cox et al found that as hurricanes increase in power, the resulting storm surge can damage more properties (Cox, Dowling, et al. 2020).

1.7. Vulnerability of Septic Systems to Rising Groundwater Levels

Seasonal variation between the dry and wet season also alters the depth of the water table. During the wet season, groundwater tables are elevated. O'Driscoll, et al. (M. A. O'Driscoll et al. 2014) found that following a hurricane "the groundwater was elevated above the drainlines". Frank, et al. identified that flood events in Levy County, Florida, had the potential to contaminate drinking water wells (Frank et al, 2019). They indicate that "Contamination can occur due to improper septic system design/siting/construction, insufficient maintenance, or inundation." One study suggests that groundwater levels and sea levels will rise at the same rate. (Rotzoll and Fletcher 2013).

Just as with rising sea levels, rising fresh groundwater levels can also reduce system performance by inundating septic tanks and drainfields, causing systems to back up or even fail to operate. Mihaly noted that in the New England states, groundwater levels are expected to rise between 31%-35% of the rate of sea level rise (Mihaly 2018). Rising sea levels can also lead to increased saline concentrations in groundwater and thus into infrastructure, disturbing the biological balance and causing maintenance problems and potential failure of treatment systems.

In 2011, Bloetscher et al noted that a residential neighborhood in South Florida served by OSTDS was found to be contributing to coastal waters during the seasonal high water table, but not during the seasonal low water table (Bloetscher, Heimlich, and Meeroff 2011). With both sea level rise pushing up groundwater levels from below, and increasing precipitation adding to groundwater levels from above, the compounding affect will significantly contribute the reduction of the vertical separation distance by as much as an additional foot between the drainfield and the groundwater levels in some locations (Mihaly 2018).

1.8.Soils

Further exasperating the biological processes are that proper attenuation of contaminants requires certain organic material in the soils. Day estimates that as much as one-third of soils in North America do not have the necessary composition to meet drainfield requirements (Day 2004). Sandy soils tend to have high hydraulic conductivity, meaning liquids move quickly through them (Soil Science Division Staff 2017). When effluent is transported through high hydraulic conductivity soils there is less time for filtration of pollutants in the vadose zone, increasing the export of pollutants to groundwater and potentially to nearby surface waters. Soil porosity is another attribute that determines the movement of effluent through the vadose zone. Porous soils generally have larger voids between the soil particles, whereas finer grained soils have less space, therefore lower porosity (Soil Science Division Staff 2017). Lower porosity could slow the transport of fluids through the vadose zone, and if there is sufficient organic matter in the soil materials, more nitrogen converion could take place, reducing the pollutant load to groundwater and surface waters.

The United States Department of Agriculture (USDA) Natural Resources Conservation Science (NRCS_ Web Soil Survey) Web Soil Survey website, the "Suitabilities and Limitations for Use, Suitabilities and Limitations Ratings, Sanitary Facilities, Septic Tank Absorption Fields (FL)" contains ratings that indicate the soils ability to assimilate drainfield effluents. These ratings include: 'Severely limited,' 'Slightly limited' and 'Moderately limited.' 'Severely limited' indicates that the soils are not appropriate for use as a septic tank drainfield, whereas 'Slightly limited' soils are appropriate for drainfields and 'Moderately limited' can be used for drainfields if appropriate measures are taken to improve the site conditions (United States Department of Agriculture 2021). Coastal environments, especially in Florida, frequently do not have sufficient organic content to completely attenuate nutrients and pollutants. Florida coastal soils are mostly sand with little to no organic content (United States Department of Agriculture 2021).

1.9.Vulnerability of Septic Systems to Compounded Threats

Understanding the vulnerability of onsite wastewater treatment systems to any one of these threats plays a critical role in taking action to resolve them. But knowing when systems are, or will become, vulnerable to multiple threats can greatly help communities develop plans to prioritize areas in order to increase resiliency. This may mean raising septic system drainfields to increase the vertical separation distance of drainfields and groundwater tables, septic system upgrades to increase nitrification, connecting to an available municipal sewer system, or building a community cluster or package plant treatment system (Diaz-Elsayed et al. 2017; Kramer et al. 2006; Wood et al. 2015).

Currently there is much research suggesting there are several threats facing OSTDS in low lying coastal areas. It is necessary to understand how when all of these threats are combined, they impact a given septic system's level of vulnerability. The focus of this study is to develop a vulnerability analysis for septic systems exposed to multiple impacts of climate change. Before discussing the goal and objectives of this work, some concepts of 'vulnerability analysis' must be defined.

'Vulnerability' as a concept has changed as climate change related vulnerability analyses have evolved over the last several decades. Presently, it is commonly defined as the 'function of the system's exposure, sensitivity and adaptive capacity to external stressors' (Fu and Peng 2019). 'Sensitivity' in this case is how much damage would a septic system suffer when exposed to SLR, storm surge and/or flooding. ‘Exposure,’ or risk, is the likelihood or possibility that the septic system would be exposed to these impacts. ‘Adaptive Capacity’ is the ability of the septic system, or in this case the property owners, the local environment, the economy, public health or other elements that might be impacted by the result of damages to a septic system, to adjust to the potential damages caused by SLR, storm surge and/or flooding. This project will use ‘Risk’ as defined here – the *likelihood* that a septic system will be *exposed* to a given threat parameter (i.e. sea-level rise, high tide flooding, storm surge, etc.). When a septic system is vulnerable it in turn presents a risk to its surrounding environment. Some of the ways in which septic systems are vulnerable and the risk this may present are discussed next.

1.10. Purpose of Research

While it is the vulnerability of the septic systems that will be analyzed, it is the value received from a properly functioning septic system that is of interest. When a system functions properly, human waste is treated so that when it is released to the environment there are no undesirable consequences of that release. When a system is functioning poorly or not at all, partially or raw sewage can negatively affect valued elements of our community. These may include the financial situation of the property owners, the property value, the local environment, the economy, public health or other elements important to the community’s residents and local leaders. These are the attributes of a properly functioning septic system that are valuable.

While OSTDS are individually owned and maintained, damages or poorly function systems could result in negative impacts to human health and the environment for the whole community. To prevent these negative consequences it is important to identify which septic systems are vulnerable to climate change related impacts.

1.11. Project Objectives

To understand the risk of septic systems in the study area to sea level rise, storm surge and other climate change related impacts, this study uses a multi-criteria weighted vulnerability assessment method to quantify the risk to each individual septic system. To supplement the vulnerability scores and aid in development of adaptation planning, nitrogen export loading to area waterbodies will be modeled. To assist communities with plan development, information on wastewater treatment technology options, such as advanced treatment units, package plants, municipal sewer connection, composting toilets, costs and funding opportunities has been compiled to help communities to decide on a solution that fits their needs.

The objectives of this project are to:

a. Identify areas at risk from near-term sea level rise or frequent inundation from significant weather events with special attention to locations served by OSTDS

b. Calculate nutrient export estimates from OSTDS within study area c. Research, synthesize and present to stakeholders alternative wastewater treatment systems.

d. Assist area stakeholders in development of adaptation plans to increase resiliency and reduce impacts of sea level rise on nutrient exports from OSTDS.

e. Develop methodology that will be transferable to coastal regions of Florida and similar coastal areas of the US and possibly around the world.

2. METHODOLOGY

This project used a vulnerability assessment and ArcNLET modeling together to identify septic systems and areas at high risk of failure due to climate change related impacts. The vulnerability assessment results in a score for each septic system that indicates how vulnerable each septic system is to the impacts of climate change. A septic system that has the potential to be exposed to 1-foot of sea level rise has a vulnerability which can be quantified using a vulnerability assessment. Since there are several climate change related impacts that can affect septic systems, we can use a multi-criteria vulnerability assessment to capture each of those vulnerabilities into one score that represents the total vulnerability of the septic system.

ArcNLET is a tool designed to be used in the ESRI ArcGIS software to estimate nitrogen loading from source septic systems to nearby waterbodies. The tool uses a Digital Elevation Model (DEM) that is 'smoothed' and used to represent the groundwater surface. The tool also uses hydraulic conductivity and porosity data to model how nitrogen moves through soils and groundwater to eventually make its way out to nearby waterbodies. The tool produces 'particle pathway' vector file and attribute table, and a 'plume' raster with attribute table. The attribute tables contain valuable information about the receiving waterbody for each septic system, the length of plume and length of particle pathway and total loads to waterbodies.

Using the vulnerability assessment together with ArcNLET outputs can identify septic systems that have high vulnerabilities and are contributing nitrogen to waterbodies. A septic system that has high vulnerability and is contributing nitrogen to waterbodies would be an ideal candidate for conversion to a municipal sewer system. This would eliminate the vulnerability of the septic system and the nitrogen load to the waterbody. When the vulnerability assessment and ArcNLET are used together for a regional area of septic systems and a range of vulnerability assessment scores are calculated and the nitrogen loading of all septic systems is modeled, septic systems can be prioritized: high vulnerability score and high nitrogen contribution would be first for conversion to a municipal sewer system vs a lower vulnerability score with moderate nitrogen loading to waterbodies.

Because residential septic systems may be clustered in subdivisions, it can be advantageous for municipalities to understand the subdivision level vulnerability of the cluster of septic systems and the nitrogen loading those septic systems contribute to nearby waterbodies. Using subdivision data from the county property appraiser's office makes it possible to identify which parcels, and therefore septic systems, are in the same subdivision. We can then calculate the average of all the vulnerability scores of all the septic systems in that subdivision to understand the subdivision level vulnerability of septic systems to climate change impacts. ArcNLET does not provide the nitrogen loading estimate for each individual septic system but it does indicate which septic systems are contributing to nearby waterbodies (see section 3.3 for a full explanation). Using this subdivision level information for vulnerability and nitrogen loading can further inform municipalities of which subdivisions might be prioritized for projects designed to reduce septic system vulnerability and nitrogen loading to waterbodies.

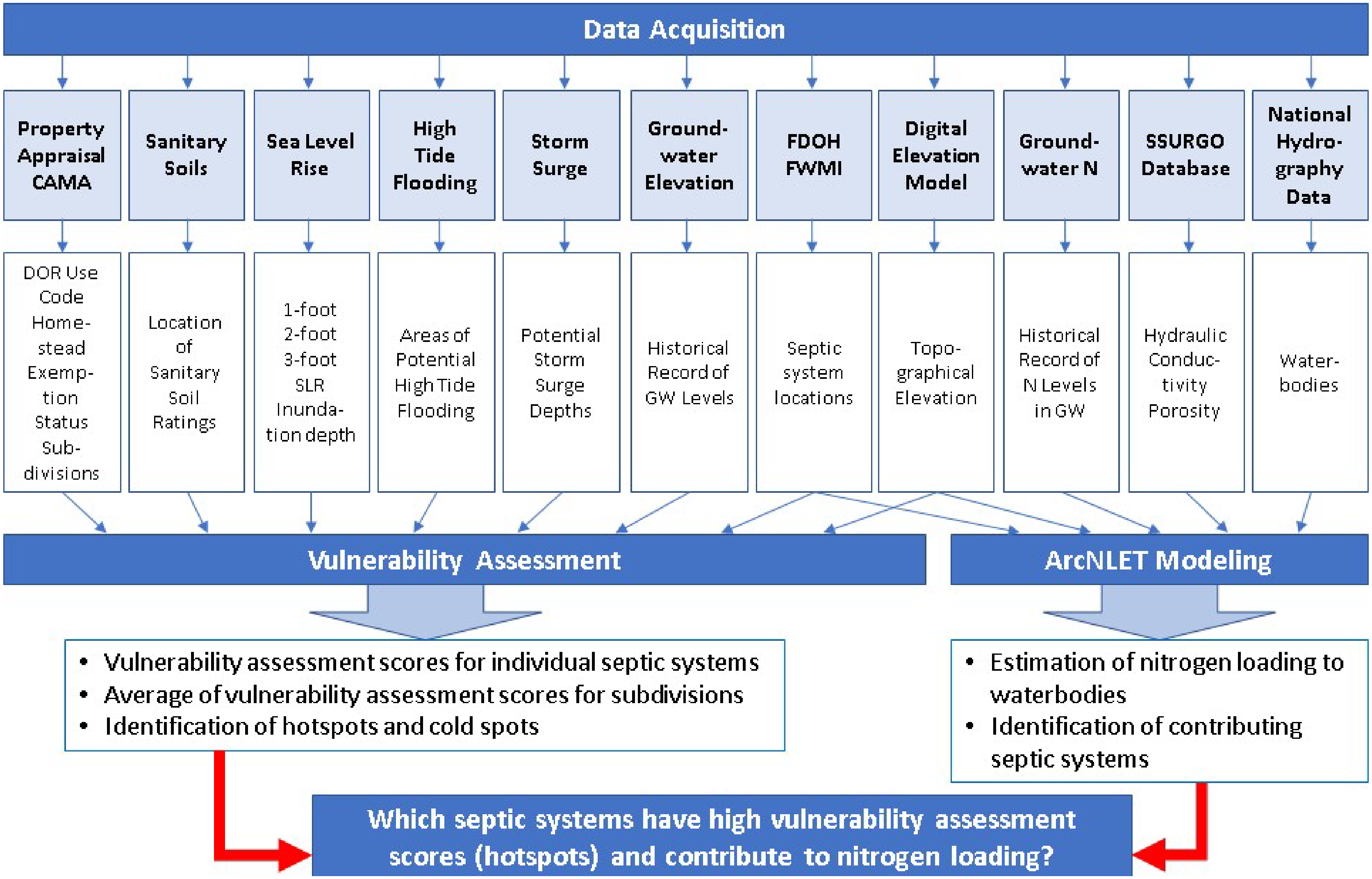

Figure 2.1 Methodology Diagram. Data acquisition gathered publicly available data to transform into necessary information. These were then used by the vulnerability assessment and/or ArcNLET modeling. Outputs from the vulnerability assessment and ArcNLET modeling is used together to identify systems with high vulnerability and are also contributing to nitrogen loading to waterbodies.

Together, the vulnerability assessment and the ArcNLET modeling can provide key information to municipal and wastewater authorities about climate change related threats facing septic systems in their area and help prioritize upgrade or conversion projects. Figure 2.1 depicts the methodology for this project, beginning with data acquisition, transformation, application and, lastly, interpretation.

2.1.Study Area

The City of St. Augustine's water/wastewater service area, located in St. Johns county in northeast Florida is the pilot location for this work (Figure 2.2). The water/wastewater service area, larger than the city's municipal boundary (Figure 2.3), is intersected by eight waterbodies that are identified as Impaired by FDEP ("Verified List Waterbody Ids (WBIDs)" n.d.). The impairments include bacteria (6 waterbodies), fecal coliform (1 waterbody) and dissolved oxygen % and chlorophyll-a (both in 1 waterbody) (Figure 2.3).

Using Florida Department of Health, Florida Water Management Inventory data for St. Johns County, St. Johns County Property Appraiser CAMA, wastewater sewer infrastructure data provided by the city of St. Augustine, and by review of city staff, 2,938 residential septic systems were identified within the study area (Figure 2.4). The City has relatively low elevation with minimal change (0 m – 21.9 m / 0 ft – 71.9 ft) in that elevation. Soils are mostly sandy with little organic matter making it not well suited for effluent treatment. Like many low lying coastal communities, it is subject to increasing storms resulting in more frequent flooding events and sea level rise both of which also contribute to rising groundwater levels.

Using publicly available data, datasets were created for the digital elevation model (DEM), hydraulic conductivity, porosity, waterbodies, 1-foot, 2-foot and 3-foot sea level rise, high tide flooding, storm surge and groundwater elevation. Additionally, the Sanitary Soils (FL) layer was used to identify the soil rating class for effluent processing. Table 2.1 lists the data sources and how they were used in this project. The DEM was modified to 'remove' roads and bridges where they created an artificial barrier to water flow in the raster data. Hydraulic conductivity and porosity were generated following instructions in the ArcNLET User's Manual (Rios et al. 2011). Waterbodies were generated by dissolving multiple selections from NHD datasets and manually breaking into sections that represented how particle pathways were grouping into receiving waterbodies (see Section 2.4). Zonal statistics were used to identify the median value in parcel polygons for the three sea level rise scenario rasters and the storm surge raster. Where estimates of high tide flooding intersected parcels these were noted as such. Daily groundwater elevation data was received for the period 1/1/2010 through 12/31/2021. Annual mean elevation was calculated and used to develop the rate of change (how fast groundwater elevations were rising) and a linear equation of the relationship between groundwater elevation and surface elevation from which a groundwater elevation raster was created. Data derived from all of the datasets was joined to the septic system location point layer dataset to create a master dataset of all data values for all septic systems. This dataset was used for the vulnerability assessment, calculations of subdivision average vulnerability assessment score, number of septic systems in subdivisions, density of septic systems in subdivisions and as the source location layer for ArcNLET modeling. The master dataset was also used to extract subsets which identified which septic systems were at risk for specific climate change related impacts (see Table 5.1).

Figure 2.2 Map of study area. Upper right inset shows the location of St. Johns county within the state of Florida. Center right inset shows the location of the City of St. Augustine within St. Johns county. Main map shows the city water/wastewater service area boundaries.

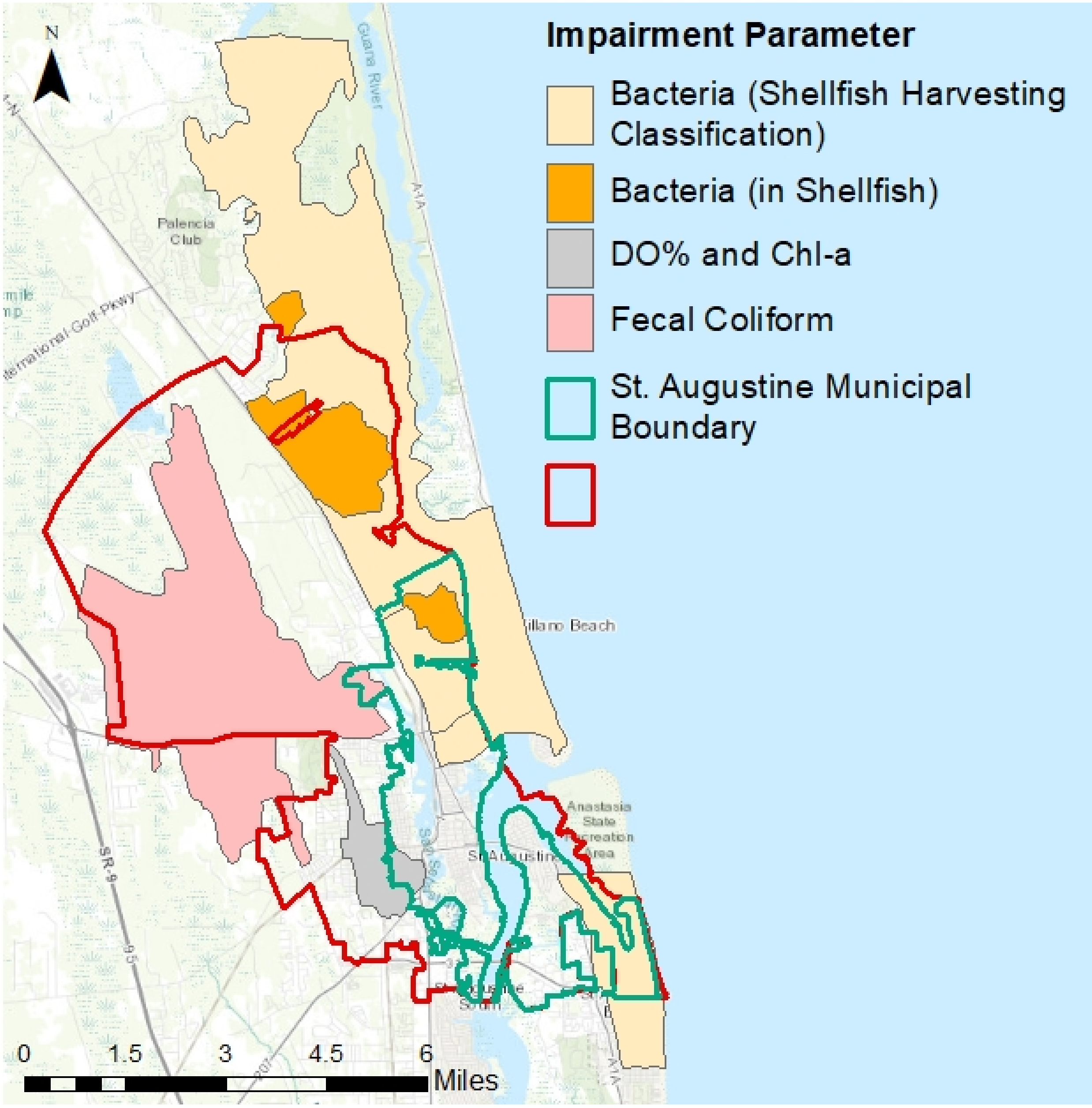

Figure 2.3 Study area with City boundary and impaired waters. The study area, the City of St. Augustine water/wastewater service area, (red boundary) covers a larger area than the city municipal boundary (green boundary). Also, the study area is intersected by eight waterbodies that have verified impairments including bacteria, fecal coliform, dissolved oxygen (%) and chlorophyll-a.

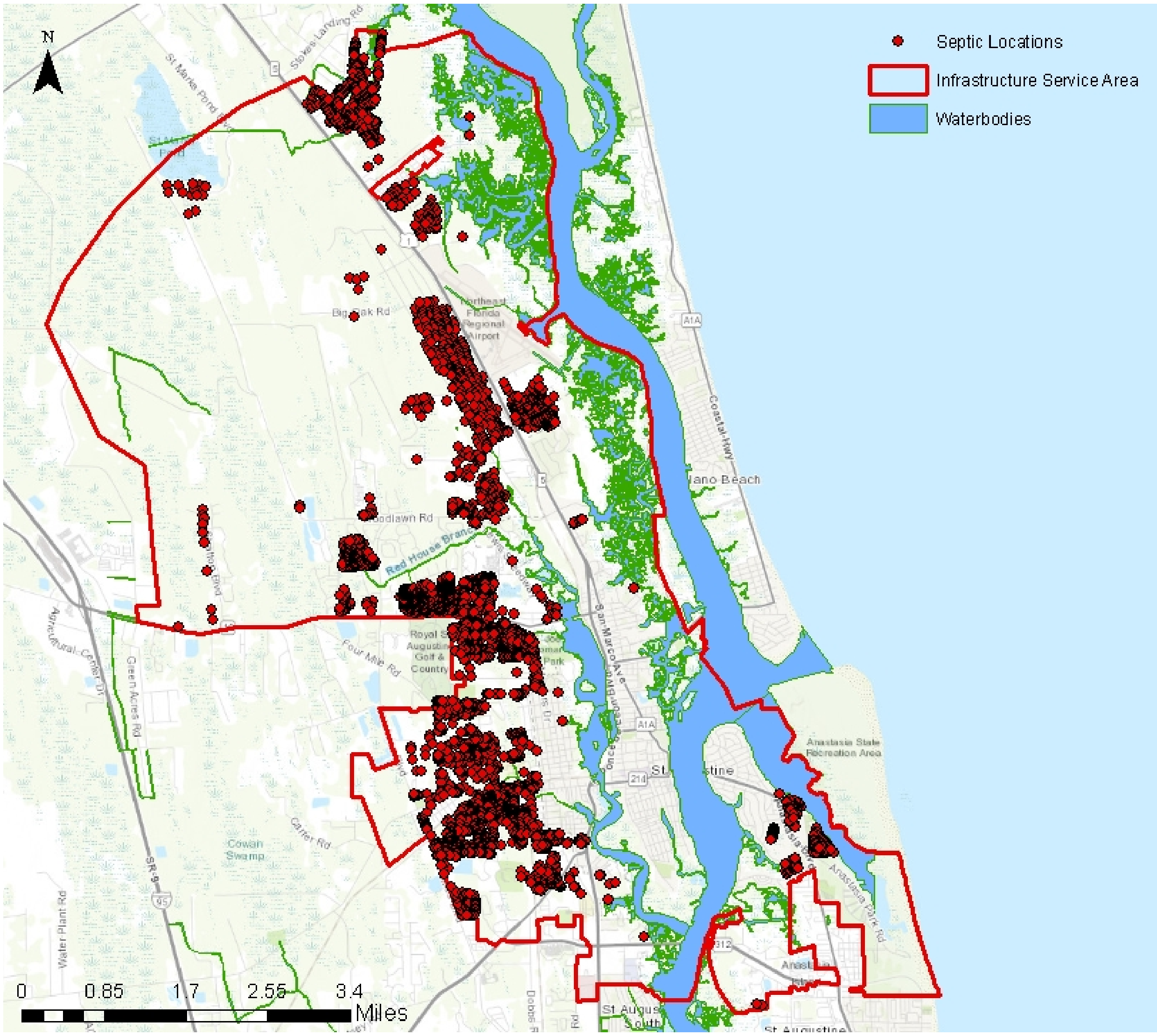

Figure 2.4 Septic systems in study area. There are 2,938 residential septic systems in the study area.

Table 2.1 Table of Data elements, sources and acquisition information. Data used in this project were acquired from publicly available sources and were used in the vulnerability assessment and/or ArcNLET modeling.

Element	Source	Acquisition Info	Where used
Septic Systems (Source Locations)	Locations of septic systems (shapefiles) at the parcel level is available from the Florida Department of Health, Florida Water Management Inventory: http://www.floridahealth.gov/environmental-health/onsite-sewage/research/flwmi/index.html	Shapefile, Last updated 2018	Vulnerability Assessment and ArcNLET modeling
St. Johns County Property Appraiser CAMA Data	Property characteristics such as DOR code, exemption status and subdivision were extracted from CAMA (Computer Assisted Mass Appraisal) files. https://www.sjcpa.us/formsdata/	CAMAData.mdb and CAMADataSup.mdb were Downloaded ½/2021	Vulnerability Assessment and ArcNLET modeling
Digital Elevation Model	A DEM shapefile is available from NOAA SLR Viewer https://coast.noaa.gov/slrdata/	5 m resolution, last updated 6/29/2020	Vulnerability Assessment and ArcNLET modeling
Hydraulic Conductivity and Porosity	SSURGO database available from the USDA Natural Resources Conservation Services Web Soil Survey	Polygon shapefile and Access database downloaded 1/7/2021	ArcNLET modeling
Waterbodies	National Hydrography Database provided by the United States Geologic Survey	Polygon and polyline shapefiles downloaded 1/7/2021	ArcNLET modeling
Sea Level Rise	Both Sea Level Rise and High Tide Flooding shapefiles are available from NOAA SLR Viewer https://coast.noaa.gov/slrdata/	5 m resolution, last updated 6/29/2020	Vulnerability Assessment and ArcNLET modeling
High Tide Flooding	Both Sea Level Rise and High Tide Flooding shapefiles are available from NOAA SLR Viewer https://coast.noaa.gov/slrdata/	5 m resolution, last updated 6/29/2020	Vulnerability Assessment and ArcNLET modeling
Storm Surge	NOAA provides data on storm surge from https://www.nhc.noaa.gov/nationalsurge/#data	November 2018 (v2), .geotiff format	Vulnerability Assessment and ArcNLET modeling
Groundwater	Groundwater levels available from St. Johns River Water Management District upon request	Excel file with lat/long, provided 10/13/2020	Vulnerability Assessment
Sanitary Soils	Soil data shapefiles are available from the Web Soil Survey https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx	Shapefiles, Downloaded 8/20/2020	Vulnerability Assessment

2.2.Vulnerability Assessment

The vulnerability assessment methodology followed that of the Oosting and Joy study (A GIS-Based Model to Assess the Risk of On-Site Wastewater Systems Impacting Groundwater and Surface Water Resources, 2011) which uses a risk rating designation for each parameter, and a risk importance value determined by key stakeholders. While the Oosting and Joy study used multiple parameters relevant to the systems themselves (soils, lot sizes, distance to surface water, floodplain, system age) it did not include any parameters relevant to climate change or specific to low-lying coastal areas.

In a meeting with CoSA staff, staff discussed available parameters, how to assign ranks and which weights to choose. CoSA staff chose 3 single parameters and 1 combined parameter: Sanitary soils, groundwater rise rate, sea level rise potential and parcel elevation combined with storm surge potential. These parameters were selected because they represented imminent and chronic risks. For example, staff felt that sanitary soils and rising groundwaters were risks that would be experienced more frequently and with higher consequences than high tide flooding which, while they currently experience 12-16 times per year, are events that appear and recede, whereas the soils and groundwater conditions are present and persistent.

After selecting the parameters, the value of each parameter received a 'risk rating' based on the likelihood of exposure that parameter presents to septic systems. For example, if a septic system is found to be within an area of 1-foot potential sea-level rise inundation, the risk of exposure has a higher likelihood than a 3-foot potential sea-level rise and so the risk rating will be 'high' and will be assigned a value of 5. If a septic system is found to be within an area of 3-foot sea-level rise, the risk rating will be 'low' and will be assigned a value of 1.

To assign the risk ratings for sanitary soils, staff noted the three designations in the "Sanitary Soils (FL)" layer ('Slightly Limited,' 'Moderately Limited,' and 'Severely Limited') and assigned them to the ratings 1, 3 and 5 respectively. Severely Limited soils are soils that are not suitable for processing septic system effluents due to one or more characteristics that result in ineffective treatment of effluents. These characteristics may include high permeability, short distance to wet season groundwater levels, bedrock or other limiting component, or areas susceptible to flooding. Soils in and around the city fall mostly within the 'Severely Limited' limitation rating for a number of reasons. The area is susceptible to frequent flooding from high tides and precipitation events, has high hydraulic conductivity and porosity, and short distance to groundwater levels. Because soil characteristics in the area are problematic for effectively processing effluent from septic systems, CoSA staff felt the soil limitation ratings were an important parameter in the vulnerability assessment.

CoSA staff has been aware that groundwater levels were rising but have been fiscally limited for any in depth monitoring. Groundwater level data was obtained from the St. Johns River Water Management District (SJRWMD) for the whole of St. Johns County. Sixteen monitoring stations were included in the dataset. Two of those stations fall within the study boundary. Fifteen stations had a continuous 11 year record of monitoring, 1 station had regular monitoring since August 2020. It was discussed whether or not to try and install new groundwater monitoring stations within the study area to gather additional data. Unfortunately, no resources were available to support more stations. The data received from SJRWMD provided evidence of rising ground water levels over the 11-year period and when combined with elevation data indicates that the distances between groundwater levels and elevation levels ranges from 0.5m – 2.7m and is rising at rates between 0.04 and 0.1 m per year meaning many areas may experience groundwater inundation of drainfields sooner than they may experience sea level rise. Staff felt this is a clear threat to septic systems. To assign rating values to rising groundwater levels, staff decided to divide the range of rise (0.04-0.1m) equally into the 5 rating bins resulting in 0.04m rise to 0.05 m rise equals a rating of 1, 0.05 to 0.07 is 2, 0.07 to 0.08 is 3, 0.08 to 0.01 is 4 and anything above 0.01 is 5.

The storm surge/elevation parameter was selected because low lying parcels have experienced much storm surge flooding from hurricanes and significant storm events. CoSA staff decided to bin elevation levels at 7-feet (2.1336 m), 10-feet (3.048 m), and greater than 10-feet. The 7-foot elevation represents the 'tipping point' where parcels at or below 7 feet of elevation experienced significant storm surge during hurricane's Mathew and Irma. Additionally, the 7-foot elevation designation correlates to the 100-year flood event and was adopted into the 2040 comprehensive plan to pursue flood mitigation projects at or above 7-feet of elevation. The elevation bins were assigned ratings of 5, 3 and 1 respectively and were combined with any parcel that fell within the potential category 1 storm surge area. See Table 2.4 for the full scope of risk ratings per parameter as determined by CoSA staff.

CoSA staff also discussed multiple weighting options for the four risk parameters identified. The discussion centered around which of the identified threats they felt presented the greatest (most significant) or most imminent threat. Because the soil characteristics are already in existence in the area and already present a threat to septic systems through ineffectual processing of effluents, and because rising groundwater levels are a more imminent threat than either sea level rise or storm surge for low lying elevations, these were both assigned a higher weight than the storm surge/elevation and sea level rise parameters. Although soils and groundwater levels were viewed as more immenent threats than sea level rise or storm surge for low elevations, they were still viewed as important and significant threats. Because of this, CoSA staff decided to assign the weights fairly equally: 30 for both soils and groundwater levels, and 20 for both sea level rise and storm surge for low lying elevations (Table 2.5).

The parameters, ratings and weights identified by CoSA staff were then used in a traditional weighted variable approach where the risk rating is the variable and the risk importance is the weight of that variable. The 'vulnerability score' of a septic system was determined by multiplying each parameter rank by the parameter weight and then summing the products of all weighted variables.

Table 2.2 Risk rating values for threat parameters. Parameters and risk assignments were identified by city of St. Augustine staff. These include 3 individual parameters (sanitary soils classification, rate of groundwater rise and potential sea level rise inundation) and one combined parameter (potential storm surge inundation and surface elevation). Values for each parameter were distributed across a low to high (1-5) ranking.

Risk Parameter	Low – 1	2	Medium - 3	4	High - 5
SS/Elevation (m)	Cat1 & Elevation >3.048m		Cat1 & Elevation 3.048-2.1336m		Cat1 & Elevation <2.1336m
Sanitary soils classification	Slightly Limited		Moderately Limited		Severely Limited

Groundwater level 11-yr average change (m)	0.03869-0.0540	0.0540-0.0694	0.0694-0.0848	0.0848-0.0971	>0.0971
Sea-level rise	3-ft SLR		2-ft SLR		1-ft SLR

Table 2.3 Table of Weights for Risk Parameters.   Weights of each parameter as determined by city of St. Augustine staff.

Risk Parameter	Weights
SS/Elevation (m)	20
Sanitary soils classification	30
Groundwater level 11-yr average change (m) lower bound	30
Sea-level rise	20

CoSA staff decided on the parameters, ratings and weights used in the vulnerability assessment based on their experience of the climate change related impacts experienced in their area, and how these impacts might affect septic systems within their infrastructure service area. Another municipality might use different parameters, ratings and/or weights altogether depending on what climate change related impacts they are experiencing in their own area, and how these impacts may or may not affect septic systems there.

Calculating individual septic system vulnerability assessment scores is extremely useful for identifying systems at risk and for understanding which areas have higher risk and lower risk relative to each other. These scores can also be used to identify spatial groups that are at higher and lower risk and to see how those groups can be prioritized for adaptation and resiliency actions. A subdivision is a spatial group that is readily recognized by most people and is a sensible grouping because the homes in subdivisions are typically built at the same time and in the say way. Thus the homes in a subdivision are close to the same age and so would be their septic systems (excepting any miscellaneous replacements), and being together spatially lend themselves to a more efficient wastewater conversion project. Vulnerability assessment scores can be determined for the subdivision by calculating the average of the individual scores within each. This can be useful to see where subdivisions have higher vs lower risk and to consider higher scoring areas for action sooner than lower scoring subdivisions. The same is true for knowing how many septic systems are in subdivisions and what the density of septic systems is within subdivisions. Municipal staff do not always have this information readily available and the having these statistics can help staff develop project parameters such as focusing on one large subdivision with many septic systems or grouping a few smaller subdivisions together to achieve a certain amount of economies of scale for project costs.

2.3.Hotspot Analysis of Individual Vulnerability Assessment Scores

ESRI's Hotspot Analysis tool calculates the statistical significance of the clustering of high and low values. High values are hot spots and low values are cold spots. Z-values and p-values are calculated for each point. Where a point has a high z-value and a low p-value, the clustering of high values is statistically significant, and a low z-value with low p-value indicates a significant clustering of low values. Confidence values for the high and low values are used to 'bin' the results in 99%, 95% and 90% confidence levels for each high and low values. Points are considered not significant if they have a z-value near zero (ESRI 2021).

Hotspot analysis was used on the vulnerability assessment scores to assess the spatial grouping of septic systems with high and low scores. Septic systems with high scores which also show up as hotspots indicate that the high scores clustered together at that location is significant and not just a random coincidence and that the septic systems in this location are truly vulnerable to climate change related impacts. Municipalities can be confident that these should be prioritized for conversion or upgrade projects as the most critical septic systems in their jurisdiction. Septic systems with low scores that show up as cold spots should not be disregarded for action. The scoring and hot spot vs cold spot indicates which systems are more at risk than others, not that low scoring or cold spots are without risk.

2.4.ArcNLET Modeling

ArcNLET is a tool developed by Dr. Ye of Florida State University and his students for use in the ESRI Arc Desktop software to estimate nitrate exports from septic systems to surface waterbodies. The ArcNLET tool takes advantage of the Arc Desktop GIS capabilities to develop particle paths from the septic system to the waterbody using a digital elevation model (DEM) and certain soil characteristics. These results are then used to build a plume of the nitrate distribution from the system and an estimate of how much of the nitrates from the system reach the waterbody.

The first module is the 'Groundwater Flow' module (see Figure 3.2 Groundwater Flow module settings.). Here the DEM is 'smoothed' using a averaging kernel to produce a 'subdued replica' of the surface elevation to approximate the groundwater elevation layer. This simplified method is appropriate in areas of low elevation but would not be appropriate for high elevations (Shahbazi, Zand, and Todd 1968). Users can set the 'smoothing factor' to choose how much to flatten the DEM. The model assumes a 2-dimensional steady state condition in only the surficial aquifer and does not incorporate any vertical flow. The DEM is then used to estimate the hydraulic gradient. Darcy's Law is used on the hydraulic gradient, waterbody location and hydraulic conductivity and porosity characteristics to estimate flow velocity. From this, the Dupuit approximation estimates 3-dimensional flow from the 2-dimensional data to produce a velocity direction layer and a velocity magnitude layer.

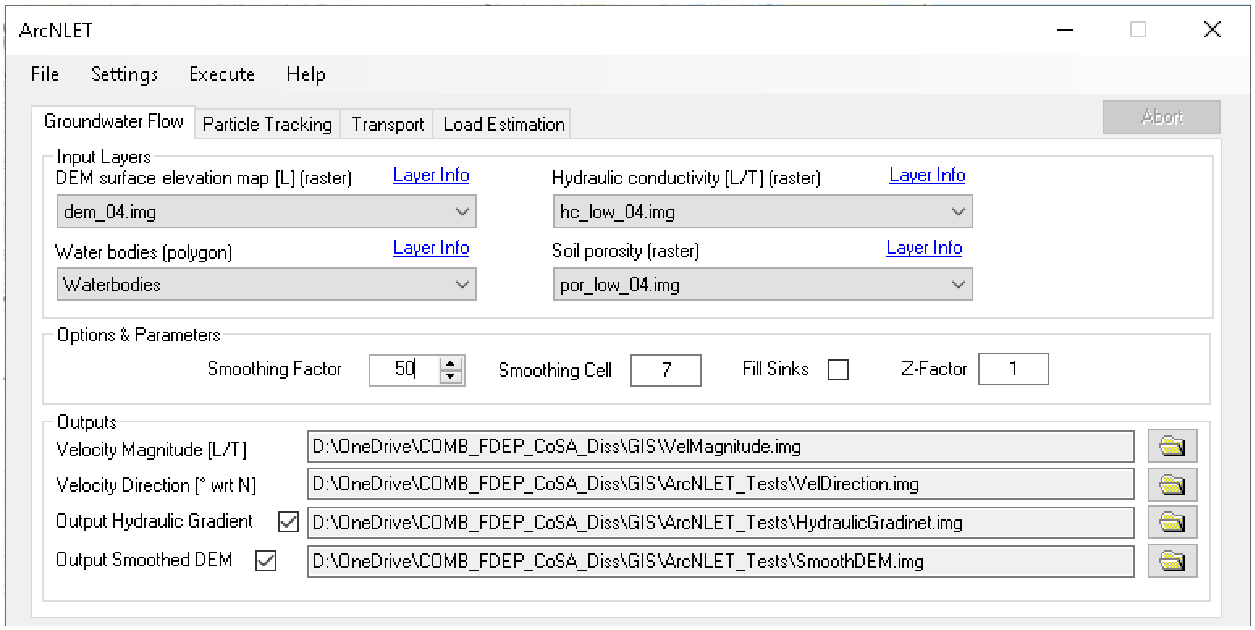

Figure 2.5 Groundwater Flow module settings. The digital elevation model, hydraulic conductivity data, porosity data and waterbody data are inputs to the groundwater flow module. Using the parameters settings (smoothing factor, smoothing cell, fill sinks and z-factor) the module creates a groundwater flow raster which then produces velocity magnitude, velocity direction and hydraulic gradient rasters.

The second module is the 'Particle Tracking' module (see Figure 3.3). This module requires the inputs of the source locations (septic system locations), waterbodies, porosity, and the velocity magnitude and direction layers produced in the Groundwater Flow module. The particle paths are developed in increments the size of which can be determined by default based on the resolution of the waterbody raster developed during processing. Additionally, users can set the maximum number of steps (default 1000) at which point the development of the particle path will be 'abandoned.' Each segment in the particle path records the porosity and velocity at the starting point of the segment (Rios et al. 2011). These segment values are then used to calculate the average velocity and porosity of the whole particle path. The values in the particle path are used to calculate the plume of the nitrate distribution from the system and an estimate of how much of the nitrates from the system reach the waterbody. The values of velocity and porosity must remain constant with a plume but can vary from plume to plume. The particle path output layer is a valuable source of information include the total length of the particle path, travel time and which waterbody each system is potentially depositing to.

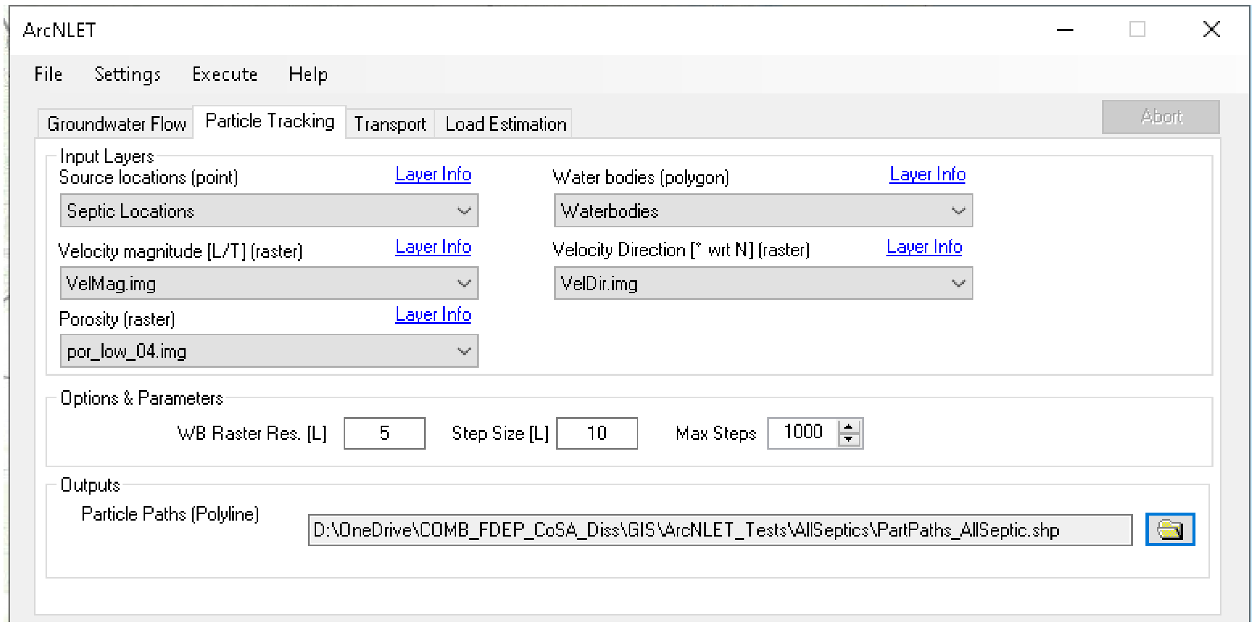

Figure 2.6 Particle tracking module settings. Using outputs from the groundwater flow module and a source location point file, the particle tracking module calculates a path from each source location to a receiving waterbody.

The third module is the 'Transport' module (see Figure 3.4). This is where the nitrate plumes are developed. This module can be extremely computing intensive because it first calculates all the plumes and holds them in temporary memory before creating the output raster of the estimated plumes. So if you have a large dataset but a small computer you may run out of memory before the raster is complete. The raster image of the plumes does not contain the nitrate values one is likely to use in a study but it is a great aid to visualization. More useful is the plume info file this module creates. It is a point shapefile that contains in the attribute table plume length, path length (the particle path length), the travel time of the path length, and the receiving waterbody ID. There are other fields in this file that suggest one can calculate the nitrate contribution from each individual septic system, however plumes frequently overlap each other, especially where density is high, and it is not possible to tease out how much is coming from which overlapping system (Ye 2021). Input layers for the Transport module include the source locations, particle paths and waterbodies. This module has many optional settings including source concentration (of ammonium nitrogen from the house to the septic system), the longitudinal and transverse horizontal dispersivities and the denitrification decay coefficient, being some of the most important. These values can also be included as fields in the source location layer if there is cause for variability among them. Additional settings include 'Min [M/t],' 'Zmax[L],' and 'z.' These settings are useful for determining how the plume develops which determines the amount of denitrification along the particle path. 'Min [M/T] is the amount of nitrate being introduced from each system in mass per time, 'z' is the vertical dimension of the plume at the source, and 'Zmax' is the maximum vertical dimension of the plume at the source. You can use either the 'Min [M/T] or the 'z.' If you choose the 'Min [M/T' you can also elect to set the Zmax but it is not required. If you do not set the Zmax value it will be automatically calculated. If you choose to use the 'z' you must also change the 'Domenico Bdy.' Parameter to "Specified Z." This option is available under the 'More >>' button. The outputs from this module, the plume info file, are used for the load estimates in the fourth module.

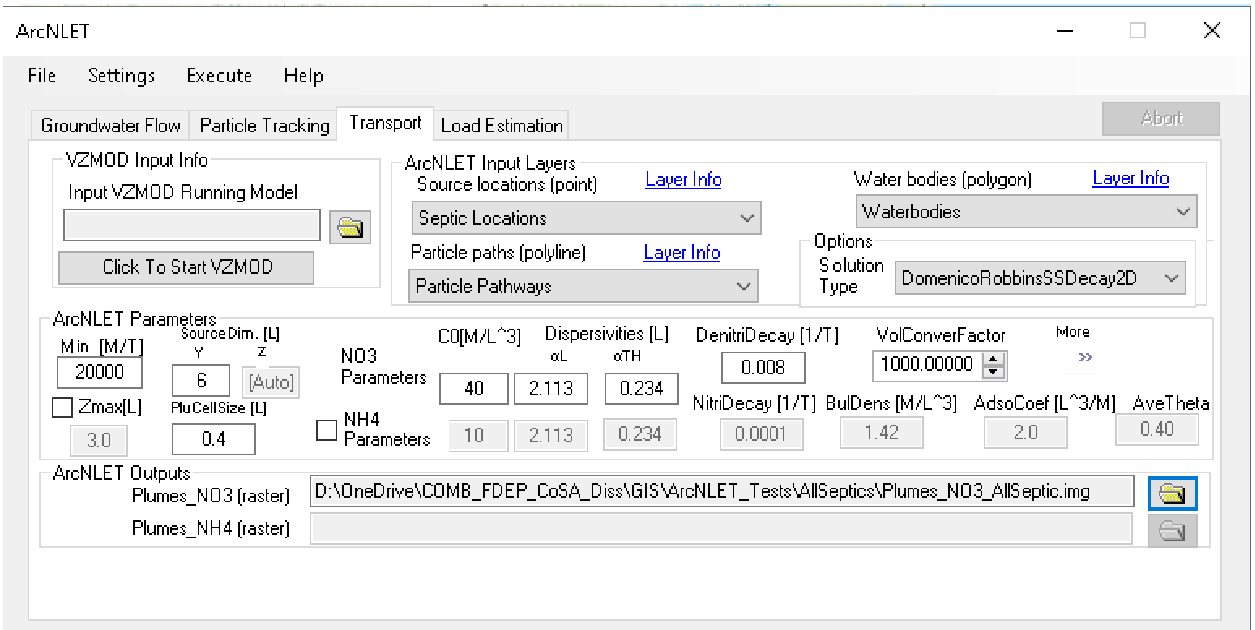

Figure 2.7 Transport module settings. Using the particle pathways developed in the particle tracking module along with the source locations and waterbodies files, the transport module calculates the dispersion of the nitrate (and ammonium if selected) plume using either default settings or settings identified by the user. An important output of the transport module is the 'plume_info' file which contains the calculations made of plume transport. The 'plume_info' file is used in the load estimation module.

The fourth module is the 'Load Estimation' module (see Figure 3.5). This module uses the plume info file to calculate the total inputs to each waterbody. The load estimation output includes the waterbody ID, the mass load output (to surface waters), mass removal rate (denitrification) and the mass input load to groundwaters. In this module you have the option to set a 'Risk Factor' which will be multiplied by the mass output load. These values can be exported to .csv. You can also export a log of all the processes performed to .csv.

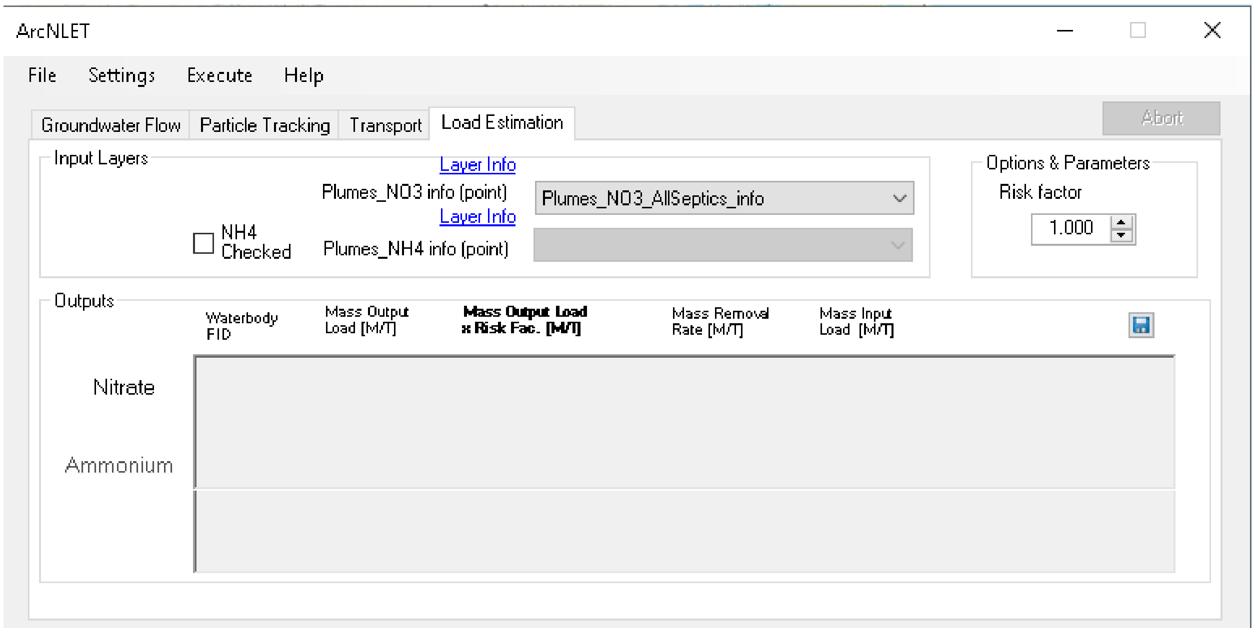

Figure 2.8 Load estimation module settings. The load estimation module uses the plume info file created in the transport module to calculate the estimated nitrogen (and ammonium if selected) exports to area waterbodies.

The tool can be operated using default settings or provides many options to customize how inputs are processed. The tool was built and calibrated based on a neighborhood in Jacksonville, Florida and these settings serve as the default settings (Rios et al. 2013). Default settings were used for the estimates because we felt the study area was similar in characteristics to the Jacksonville neighborhood to make the default settings reasonable. Due to computer constraints, only the NO3 model was performed. The images above show the settings used in each module of the tool. An image of the waterbodies and their ID number is also provided in Figure 3.6 Waterbodies with ID numbers..

Figure 2.9 Waterbodies with ID numbers. The twenty waterbodies seen here were delineated for the study area from NHD data.

2.5.Research and Report of Wastewater Treatment Technologies, Potential Costs and Funding Options

There can be several hurdles for communities and residents when switching from an onsite wastewater treatment system to other wastewater treatment technologies. The initial upfront costs are very high and there are additional monthly costs for service that residents are not accustomed to paying. For residents who live on larger parcels the connection fees can be even higher to run the extra length of line from the road to the house. An article in the Sun Sentinel notes the pushback Broward County has experienced from residents. Broward County residents are required to connect to sewer within six months of having access to the line. However in some cases, residents would rather pay the service fee than the additional cost of connecting to the lines (Barszewski 2019). Broward County Water and Wastewater Services charges single family residential customers an account fee and a minimum monthly charge based on meter size (Broward County Water and Wastewater Services 2018).

However, maintaining functional systems can be especially troubling for places like south Florida where sea level rise, including saltwater intrusion, is already impacting low lying areas on a regular basis. Chapter 64E-6 of the Florida Administrative Code requires that the base of the drainfield have a separation distance of 24” to the seasonal high water table, a minimum of 6” of soil on top of the drainfield aggregate, and at least 15’ from 3-day stormwater ponds or retention/detention areas (State of Florida 2018). Most significantly, OSTDS must be located 75’ away from drinking water wells. With rising groundwater tables in Florida, maintaining these separations will become more challenging and less certain. Submerged drainfields and OSTDS will render the systems ineffective, and storm events may cause flood waters to contaminate drinking water wells.

Solutions for septic-to-sewer, package plants, upgrades to enhanced OSTDS, or other technologies have been researched to identify alternatives to septic wastewater treatment systems. An important part of this research has been to identify the full range of costs – one-time and recurring – associated with different solutions and to identify funding mechanisms that could help utilities and residents offset big expenditures.

The results of the vulnerability assessment, the ArcNLET modeling estimates and the information in the wastewater technologies report can be used to help municipalities make decisions about adaptation and resiliency strategies. Areas of septic systems with high vulnerability assessment scores, especially if they are identified as hotspots, and where they are also contributing nitrogen to nearby waterbodies can be prioritized for conversion to more advanced treatment systems or for conversion to the sewer system, and the wastewater technologies report can provide information on what technologies are available for adaptation planning that would increase resiliency, provide an estimate of costs and also provide information about funding options to finance projects. The Wastewater Technologies report is included as Appendix A.

3. VULNERABILITY ASSESSMENT

3.1. Results of Vulnerability Assessment

This study assesses the vulnerability of single family residential septic systems in low-lying coastal communities to multiple criteria relevant to climate change related impacts. The parameters, risk and weighting values were selected by city staff as described in the methodology in section 2.2. The values identified by staff were used on the master dataset. The vulnerability assessment scores range from 30 – 460, with a mean value of 224.6 and a median of 240, in fact there were 1,892 systems with a vulnerability assessment score of 240. This was due to the predominance of 'severely limited' soils throughout the study area, along with area wide rising groundwater levels and many parcels being at high risk of storm surge at low elevation. This is significantly more septic systems with other scores such as 279 septic systems with a score of 270, and 276 septic systems with a score of 210. The distribution of scores across the study area can be seen in Figure 3.1 below. We can see areas of low scores in the south end of the study area, some in West Augustine and in Salt Run. We see areas of high scores in the north end around Stokes Creek and some moderately high values in the northern sections of the San Sebastian River and around the airport. The large group of median scores (240) follow a north-south distribution through the center of the study area. Much of these septic systems face 'severely limited' soils and rising groundwater levels but do not have low elevation challenges also. In fact, most of these parcels (1,722) had an elevation above the 7-foot (2.1 m) 'tipping point' identified by city staff. And we see in the Hotspot analysis in section 3.4, the spatial distribution of these scores follow a similar pattern.

3.2. Average Individual Vulnerability Assessment Scores for Each Subdivision

Subdivision information obtained from the St. Johns County property appraiser website provided 109 subdivisions in the study area. It is important to note that the way subdivisions are identified is not the same way as they might be identified by the average person. Property appraisal offices usually use unit or phase identifiers as part of subdivision names in their records. For example there are 4 separate 'Oak Grove' subdivisions: Oak Grove Unit 1 Unplatted, Oak Grove Unit 2 Unplatted, Oak Grove Unit 3 Unplatted and Oak Grove Unit 4 Unplatted. There are also 'Clark's Addition to New Augustine,' 'Clark's Addition to New Augustine Fla,' 'Clark Subdivision of North 1/2 of Block 25 of East 1/2 of Huertas Grant' and 'Clarks Addition #6 of Dancy Tract, Block 55.'Care must be taken when deciding whether to merge subdivision polygons based on 'like' names. In these two examples, the 4 Oak Grove polygons are all adjacent and would make a likely merge, but the 'Clarks's' polygons are not all contiguous, not even for the 2 'New Augustine' polygons and should not be merged. The 109 'subdivisions' in this study have been left unmerged. Depending on the time and scale of future projects the decision could be made to manually review and merge subdivision polygons where appropriate. Subdivisions are a useful grouping level because these are collections of properties that are contiguous, likely built at or near the same time and the existing infrastructure would be that same throughout, making them suitable as a grouping for any enhancement or conversion projects.

The average of vulnerability assessment scores within a subdivision were calculated. The scores ranged from 30 to 330 and can be seen in Figure 3.2 below. Red represents subdivisions with higher average

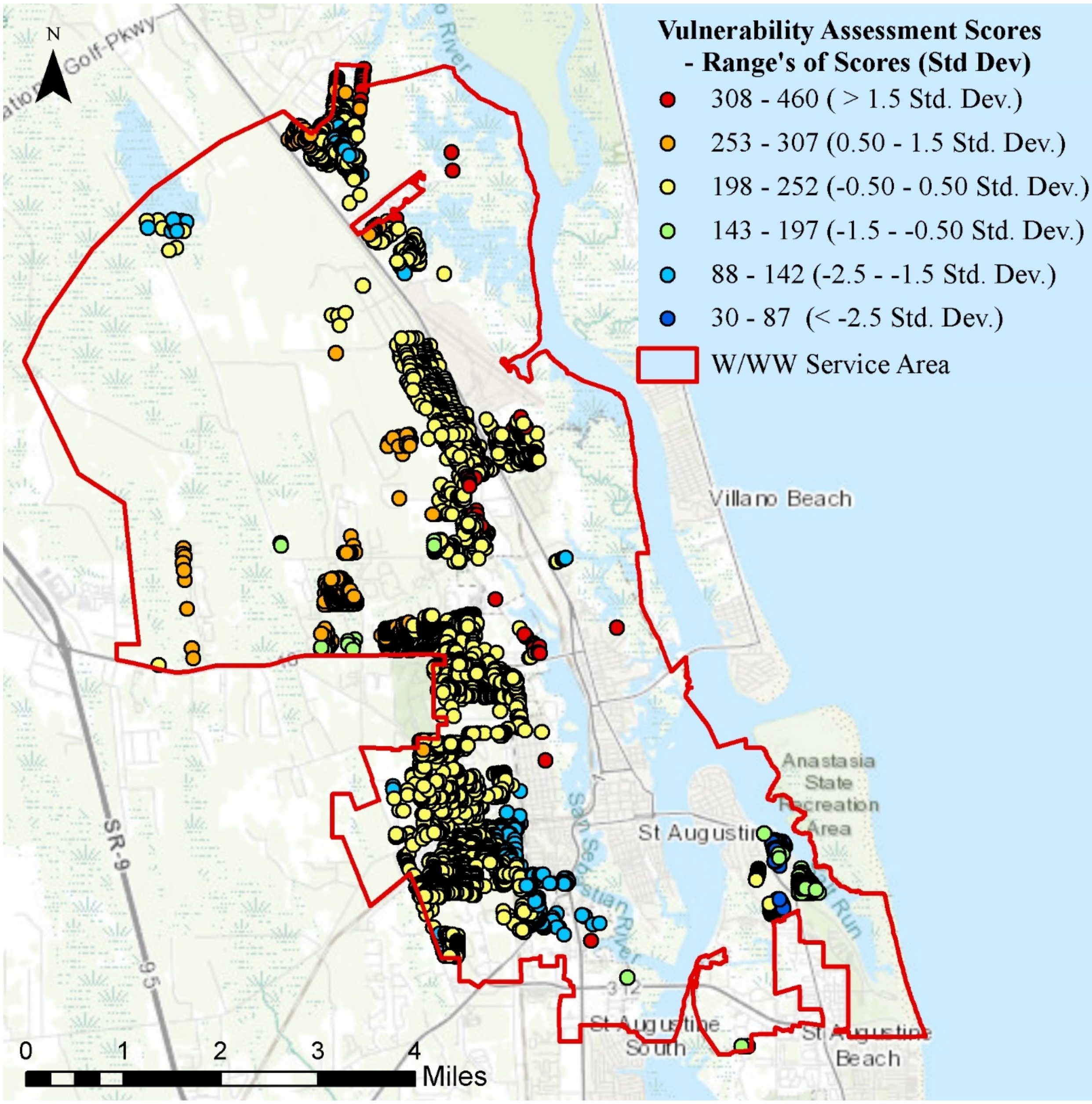

Figure 3.1 Vulnerability Assessment Scores. Vulnerability assessment scores ranged from 30-460. Low scores (blue) in the south end of the study area, represent lower vulnerability or risk from the parameters identified by city staff. Higher scores (red) in the north and central area represent higher risk to identified parameters. Numbers in parenthesis express the standard deviation from the mean of all scores.

scores and blue represents subdivisions with lower average scores. There were 2 subdivisions with scores above 295. These were the North Dixie Village subdivision (score 300) located in the north of the study area on the west end of Stokes Creek and Hildreth Back Bay Addition (score 330) located at the east end of Atlantic Ave. Most areas with lower scores are in Salt Run and West Augustine. We don't expect these distributions to be different than the individual vulnerability assessment scores, but it can be helpful to visualize them by subdivision when projects are likely to be at the subdivision level.

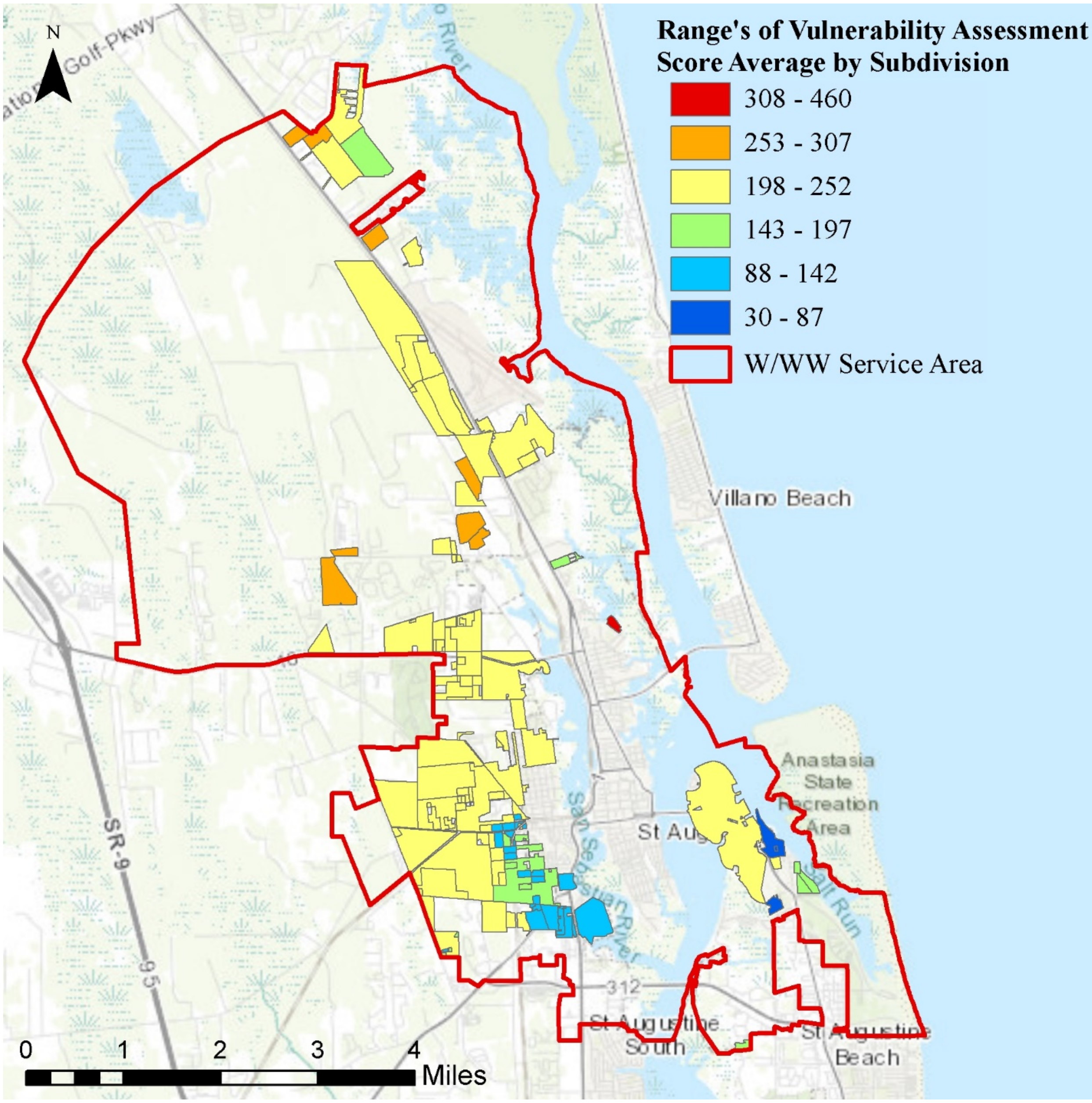

Figure 3.2 Average Vulnerability Assessment scores per subdivision. Individual scores were averaged by subdivision and can help municipalities identify subdivisions which may be appropriate for initiating projects to reduce vulnerability.

3.3.Counts and Density of Septic Systems by Subdivision

Also helpful is understanding where concentrations of septic systems might be higher or lower. Figure 3.3 displays the number of septic systems in each subdivision within the City of St. Augustine water/wastewater service area. The display identifies those having between 1 and 25 systems, 26-100, 101-200 and 201-300. Understanding where higher and lower concentrations of septic systems are located can help prioritize actions where the greatest number can be addressed the quickest. For example, the Ponce De Leon Heights (Unit 1) subdivision with 240 septic systems would be a location where more wastewater treatment improvements might be achieved quickest because of the large number of systems in one location. It is also useful to know where subdivisions with 25 or less systems are located because FDEP does not require these smaller collections to go through the effort of developing ArcNLET calculations for BMAP credit tracking (Busby 2021). And we can see in the figure that the subdivisions in the Stokes Creek area, where we have consistently seen high vulnerability assessment scores also has a high number of septic systems (101 septic systems) relative to other subdivisions. Jackson Park (153 septic systems) near the airport has also been shown to have high vulnerability scores.

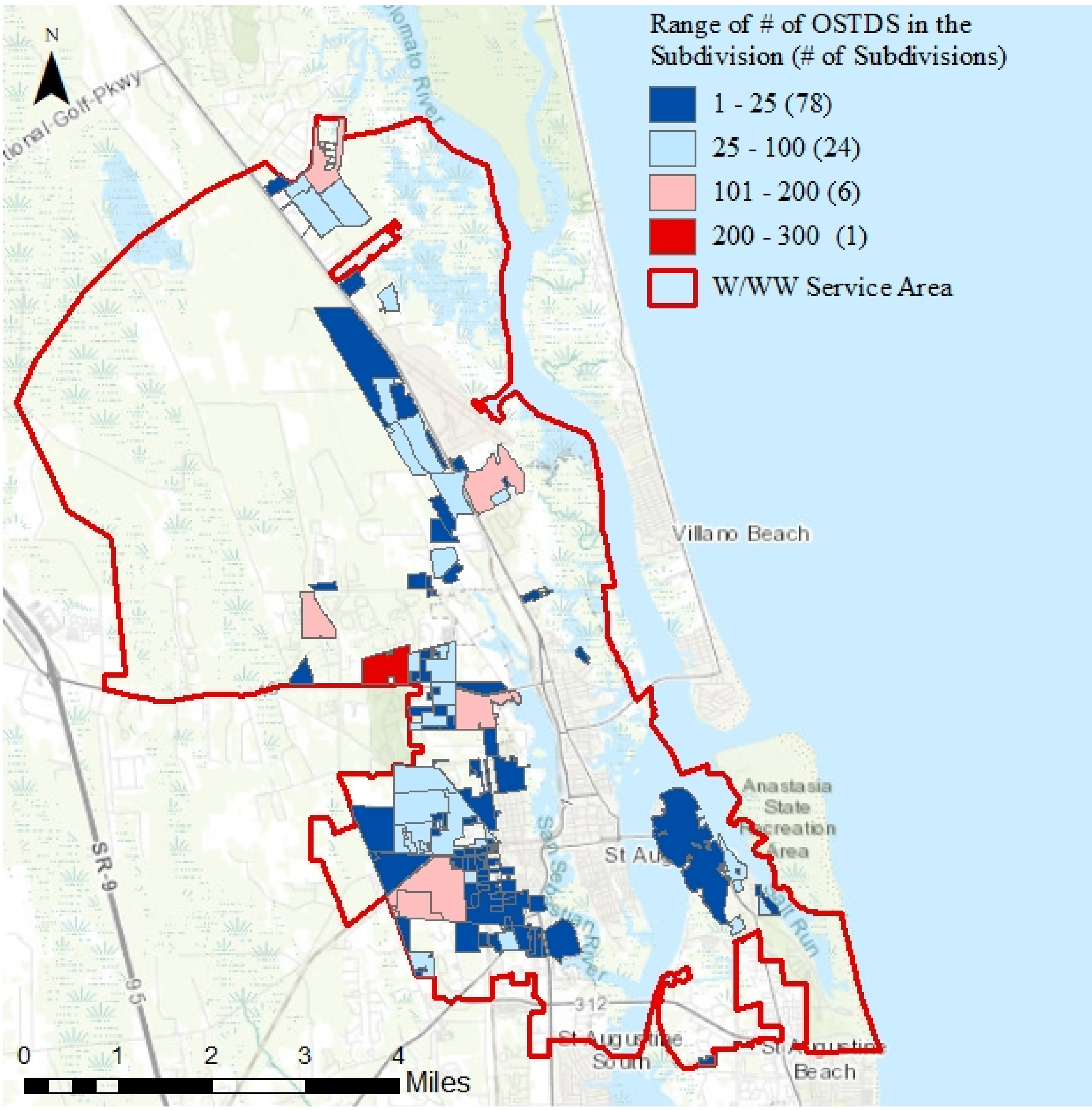

Figure 3.3 Number of OSTDS per subdivision.

Figure 3.5 below shows the density of septic systems per acre by subdivision. Areas with high density of septic systems can lead to contaminated groundwater, especially in coastal areas with sandy soils and/or soils classified as ‘severely limited.’ When there are more systems in a smaller area they may ‘overwhelm’ the soils ability to effectively process bacteria and nutrients in effluents (Mary Lusk 2018a). The higher density subdivisions shown in the map are areas where groundwaters may become contaminated and should be considered for wastewater treatment improvements.

St. Johns County Building code has identified minimum lot area and widths for private wells, septic systems and central water and sewer utilities. These are as follows:

TABLE 6.02

Minimum Lot Area and Width Based on Utilities		
Available Utilities	**Minimum Lot Area**	**Minimum Lot Width**
Private Well and Private Septic Tank	43,560 square feet	100 feet
Central Water and Private Septic Tanks	21,780 square feet	100 feet
Private Well and Central Wastewater	10,890 square feet	75 feet

B. Other Requirements

1. No multi-family Use exceeding four (4) units shall use septic tanks.

2. Farm Worker Housing is not subject to the provisions of this Section, but shall be subject to the requirements of Section 2.03.21.

3. A Minimum Lot Area of one (1) acre exclusive of lands waterward of the Mean High Water Line is required for a Single Family or Two Family Dwelling for the use of a septic system within the Coastal Area as shown on the St. Johns County Comprehensive Plan (platted or legal and documented Lots of Record existing prior to the initial effective date of this Code are exempt from this requirement).

(St. Johns County 2020)

Figure 3.4 St. Johns County Land Development Code.

We can see in Figure 3.5 below that most subdivisions have a density of 1 or 2 per acre and meet the building code design standards. Those that don’t may be older subdivisions that existed before current standards and may be grandfathered in under older standards that allowed greater density. Knowing where the possible exceptions exist (subdivisions with higher densities) can also help prioritize them for septic to sewer projects to bring them up to date with current standards and reduce the potential risks associated with these densities and climate change related risks and nitrogen exports to nearby waterbodies.

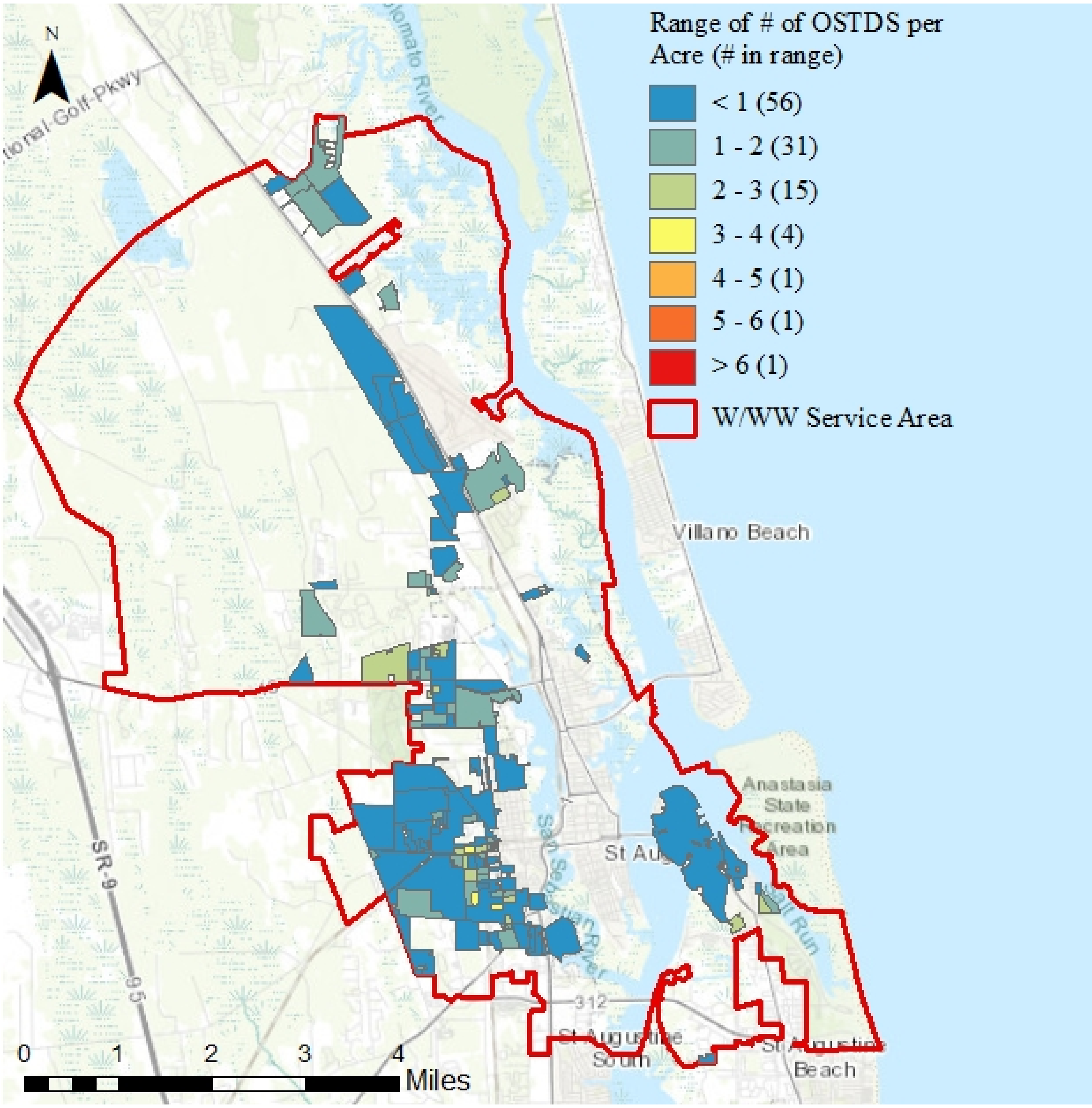

Figure 3.5 Density of OSTDS per acre by subdivision. Numbers in parenthesis are the number of subdivisions with the indicated density.

3.4.Hotspot Analysis

Similar to the distribution of vulnerability assessment scores above, the Hotspot Analysis identified areas in the north of the study area, in the norther San Sebastian River and near the airport as hot spots, with areas in the south of the study area as cold spots, and areas in the center running north and south as not significant (see figures Figure 5.6 and Figure 5.7). Twenty-eight (28) septic systems are identified as hotspots with a confidence level of 99% and are located around Stokes Creek, near the airport and in the northern stretch of the San Sebastian River. There are 233 septic systems with 99% confidence level for cold spots. These are in Salt Run and the West Augustine area (Figure 3.6). Out of the 2,938 septic systems, 2,468 were deemed to have 'not significant' vulnerability assessment scores.

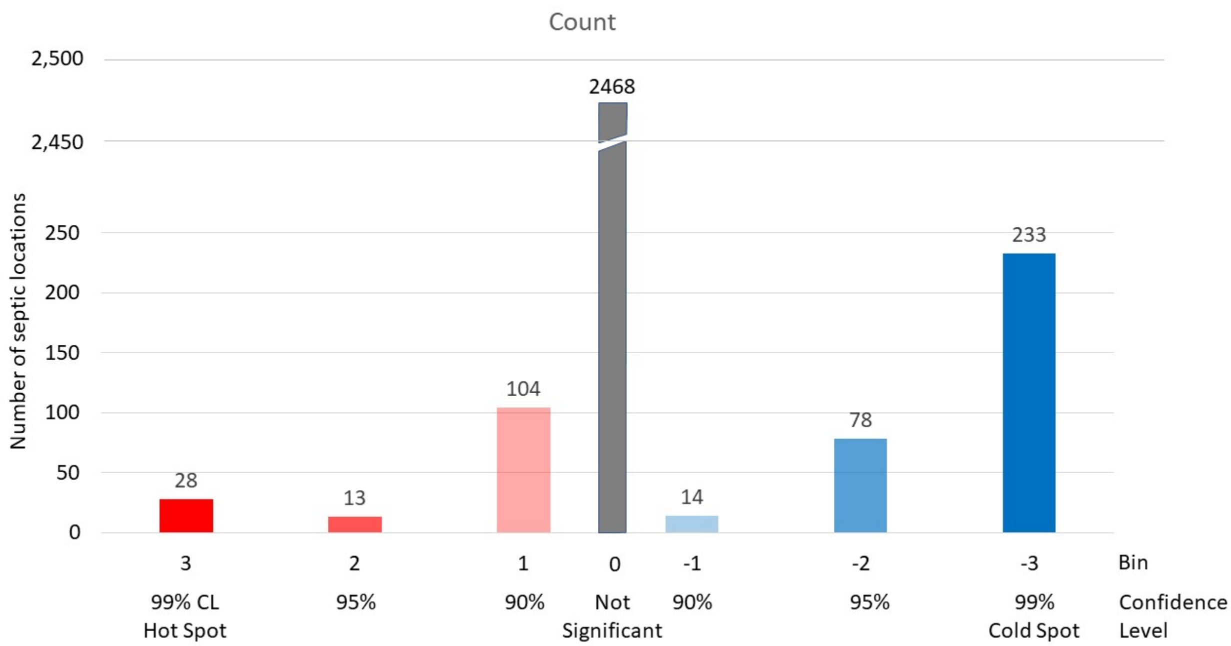

Figure 3.6 Number of Septic Locations in Hot Spot Analysis Bins. Numbers above the bars are the number of septic locations in that bin. Numbers in the x-axis show the bin number on top and the confidence level for that bin. Hotspots are bins with positive numbers and cold spots are bins with negative numbers.

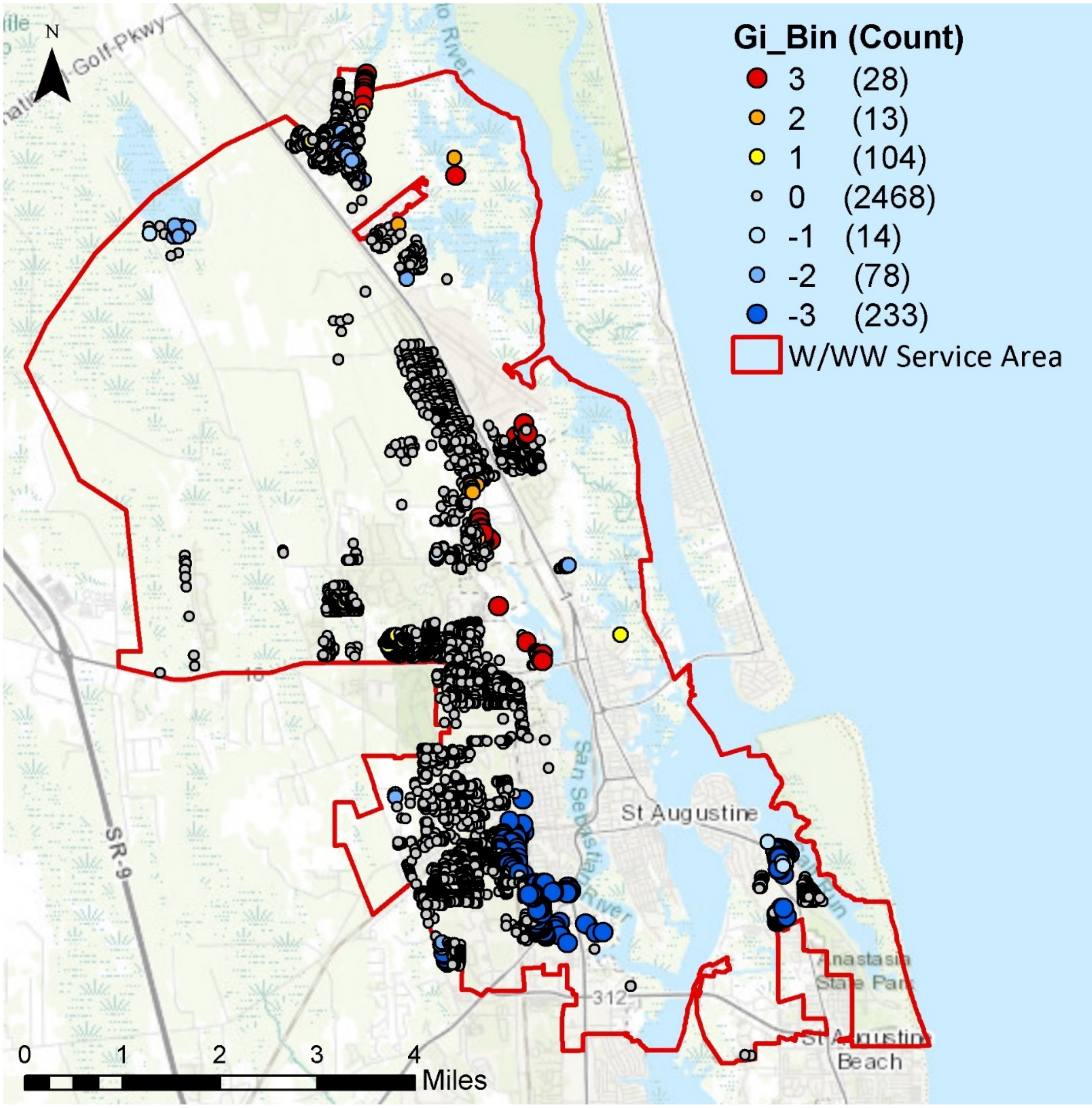

Figure 3.7 Map of Hotspot Analysis Results.

4. ArcNLET Modeling

4.1. ArcNLET Modeling Results

As discussed in the methodology, section 2.4, ArcNLET is a tool used in ArcGIS Desktop software to estimate the nitrogen (nitrates and ammonium) exports of septic systems to nearby waterbodies. The tool uses a digital elevation model (DEM), layer of relevant waterbodies, raster images of hydraulic conductivity and porosity, and a 'source layer' of septic system locations. These inputs are used to estimate the export of ammonium from septic systems to the unsaturated soil below the drainfield and estimates of nitrates through groundwater to surface waters. For this project these outputs are used to supplement vulnerability assessment scores such that septic systems, or areas of septic systems, with high vulnerability assessment scores which are also contributing these nitrogen exports to area waterbodies should be prioritized for action such as septic to sewer conversion to reduce the area vulnerability of potential septic system failure and reduce nitrogen exports to area waterbodies. To provide further insight into the demographics of area septic system facing specific climate change related vulnerabilities and other relevant vulnerabilities, the master dataset of 2,938 residential septic systems was broken down into a series of subsets based on these vulnerability factors. Table 4.1 below lists the subsets and the number of septic systems in each subset.

Table 4.1 List of Subsets and Number of Septic Systems in Subset.

Layer	Systems per Layer
All OSTDS in the study area	2938
OSTDS within the 1-foot SLR scenario	7
OSTDS within the 2-foot SLR scenario	14
OSTDS within the 3-foot SLR scenario	48
OSTDS at risk of increased flooding	87
OSTDS at risk for Storm Surge	58
OSTDS with severely limited soils	2557
Non-homesteaded parcels with OSTDS	1203
Non-homesteaded parcels with OSTDS within the 1-foot SLR scenario	2
Non-homesteaded parcels with OSTDS within the 2-foot SLR scenario	8
Non-homesteaded parcels with OSTDS within the 3-foot SLR scenario	23
Non-homesteaded parcels with OSTDS vulnerable to HTF Flooding	22
Non-homesteaded parcels with OSTDS vulnerable to Storm Surge	22
Non-homesteaded parcels with OSTDS with severely limited soils	1019

These parameters were chosen because they highlight the various climate change related risks (sea level rise, increased flooding and storm surge), or, in the case of severely limited soils, present specific threats to the effective operation of septic systems and impacts the amount of nitrogen that might be released to area waterbodies.

Outputs for each subset are provided below with an image of septic locations and particle paths. The tables show the Waterbody ID that is receiving the input (reference Figure 2.9 to locate the waterbody), how many septic systems are contributing to that waterbody, and the Mass Output Load (amount of nitrate (NO_3)) entering that waterbody in lbs/yr. These tables are sorted by the Mass Output Load column from highest load to lowest load. Note that while some septic systems may meet the criteria of the subset and will have a particle pathway that extends to an area waterbody, not all will contribute nitrate loading to a waterbody because they are far enough away that their outputs are fully attenuated before reaching a waterbody.

4.2.All OSTDS in the study area

Table 4.2 ArcNLET modeling estimates for all OSTDS in the study area.

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
10	46	1,290.60
12	20	592.88
2	29	380.97
5	4	114.86
8	11	79.80
4	5	45.44
7	2	42.38
13	2	16.78

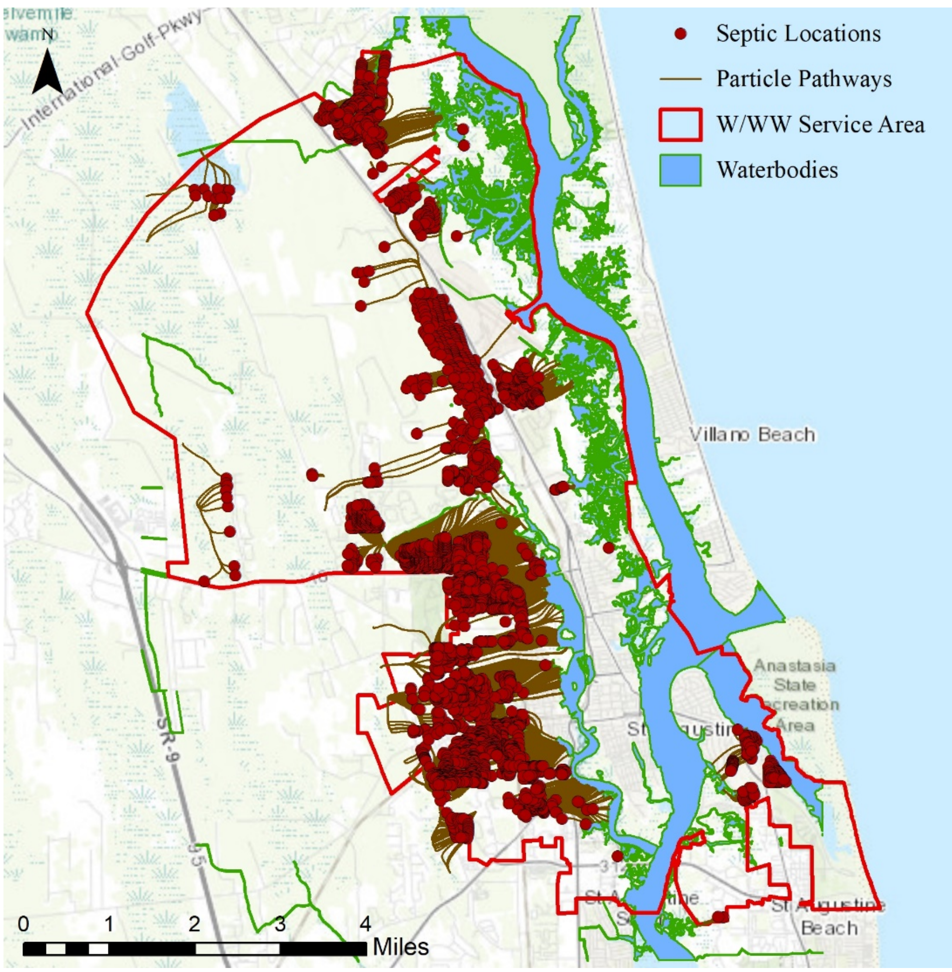

Figure 4.1 OSTDS locations and particle pathways for all OSTDS in study area.

4.3.OSTDS within the 1-foot SLR scenario

Table 4.3 ArcNLET modeling estimates for OSTDS within the 1-foot SLR scenario

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
5	2	60.23

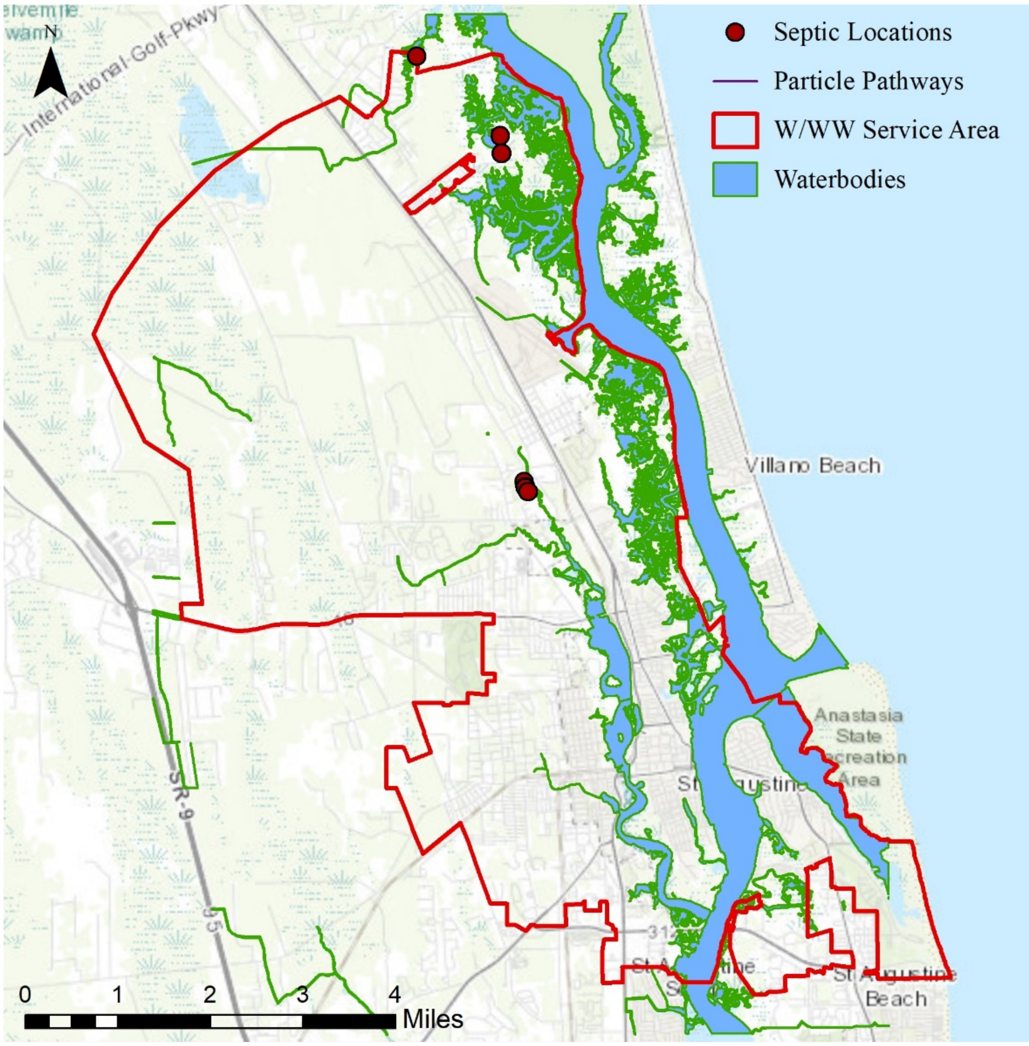

Figure 4.2 OSTDS locations and particle pathways for OSTDS within the 1-foot SLR scenario

4.4.OSTDS within the 2-foot SLR scenario

Table 4.4 ArcNLET modeling estimates for OSTDS within the 2-foot SLR scenario

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
5	2	60.23

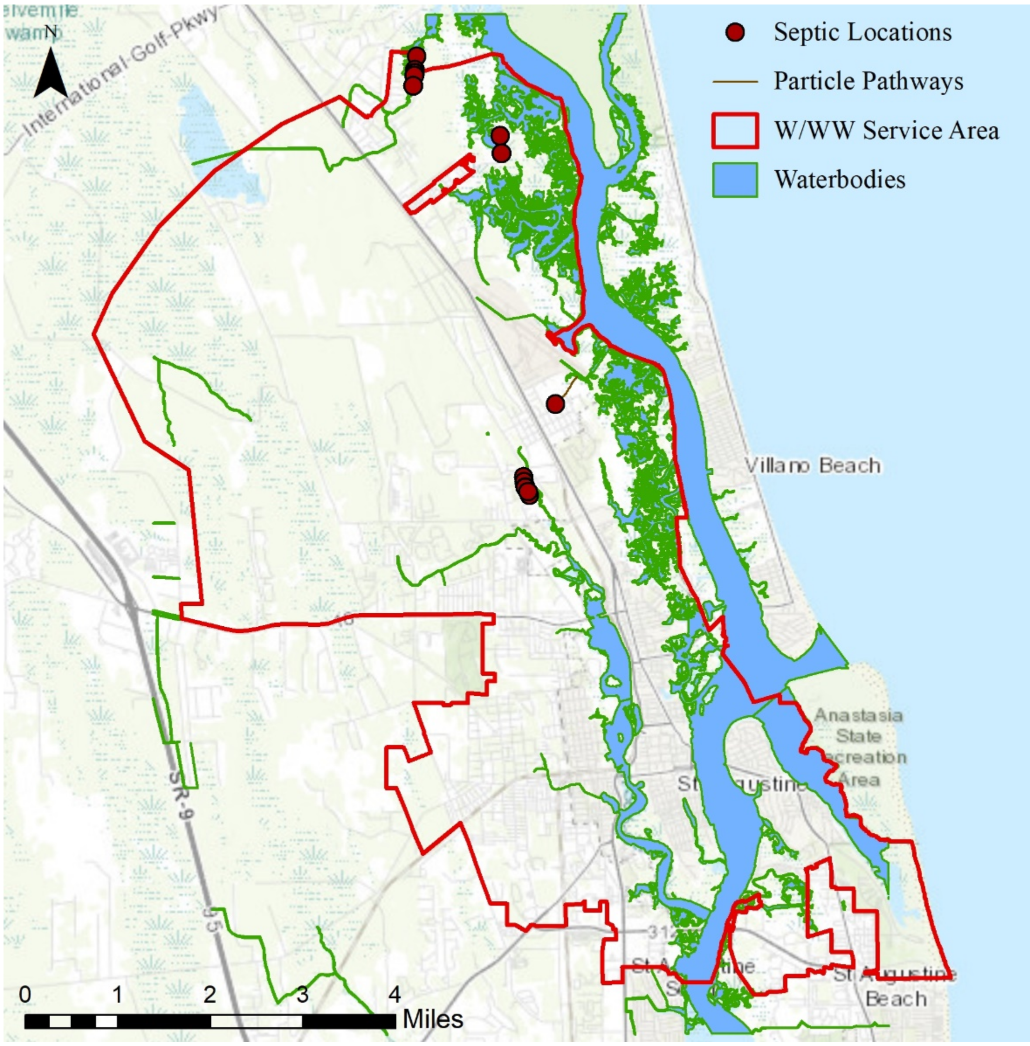

Figure 4.3 OSTDS locations and particle pathways for OSTDS within the 2-foot SLR scenario

4.5.OSTDS within the 3-foot SLR scenario

Table 4.5 ArcNLET modeling estimates for OSTDS within the 3-foot SLR scenario

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
5	2	60.23
7	2	42.38
12	2	27.89
13	1	10.24

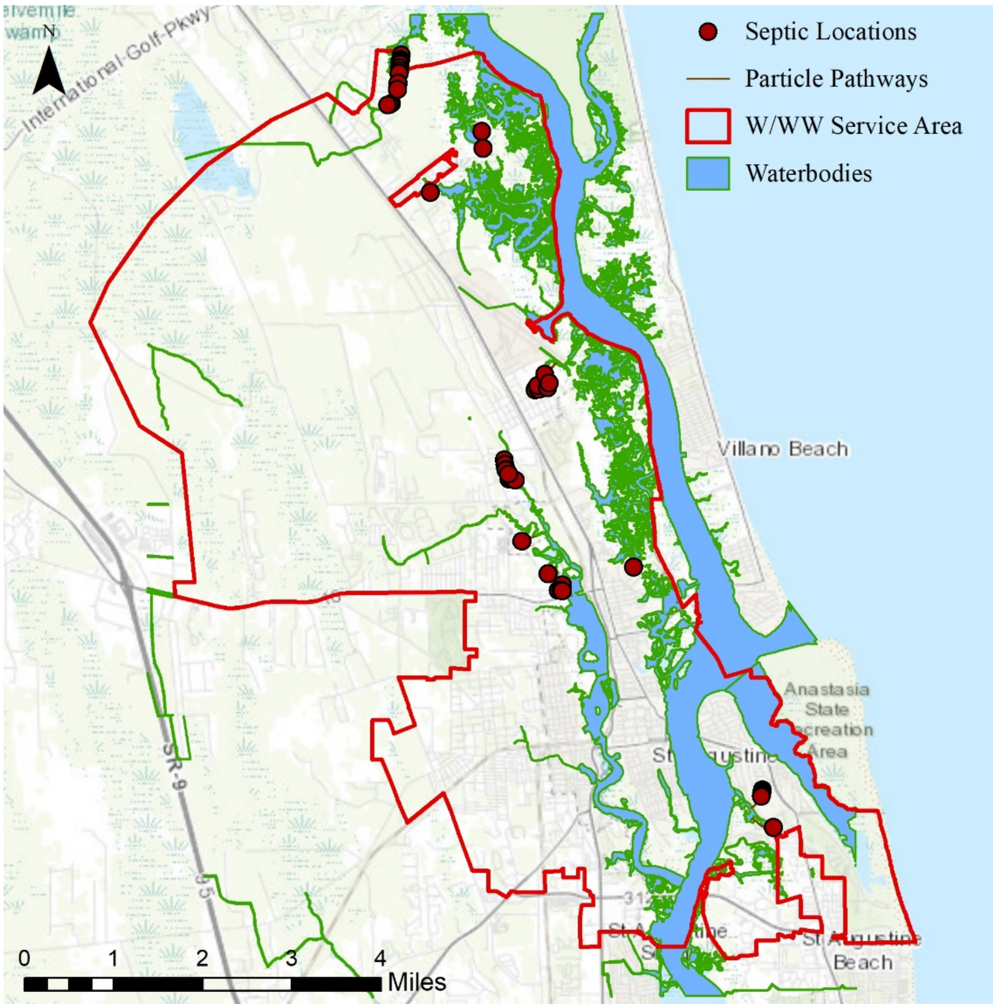

Figure 4.4 OSTDS locations and particle pathways for OSTDS within the 3-foot SLR scenario

4.6.OSTDS at risk of increased flooding

Table 4.6 ArcNLET modeling estimates for OSTDS at risk of increased flooding

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
10	5	564.05
12	8	111.67
5	3	100.26
13	2	16.78
2	1	9.46

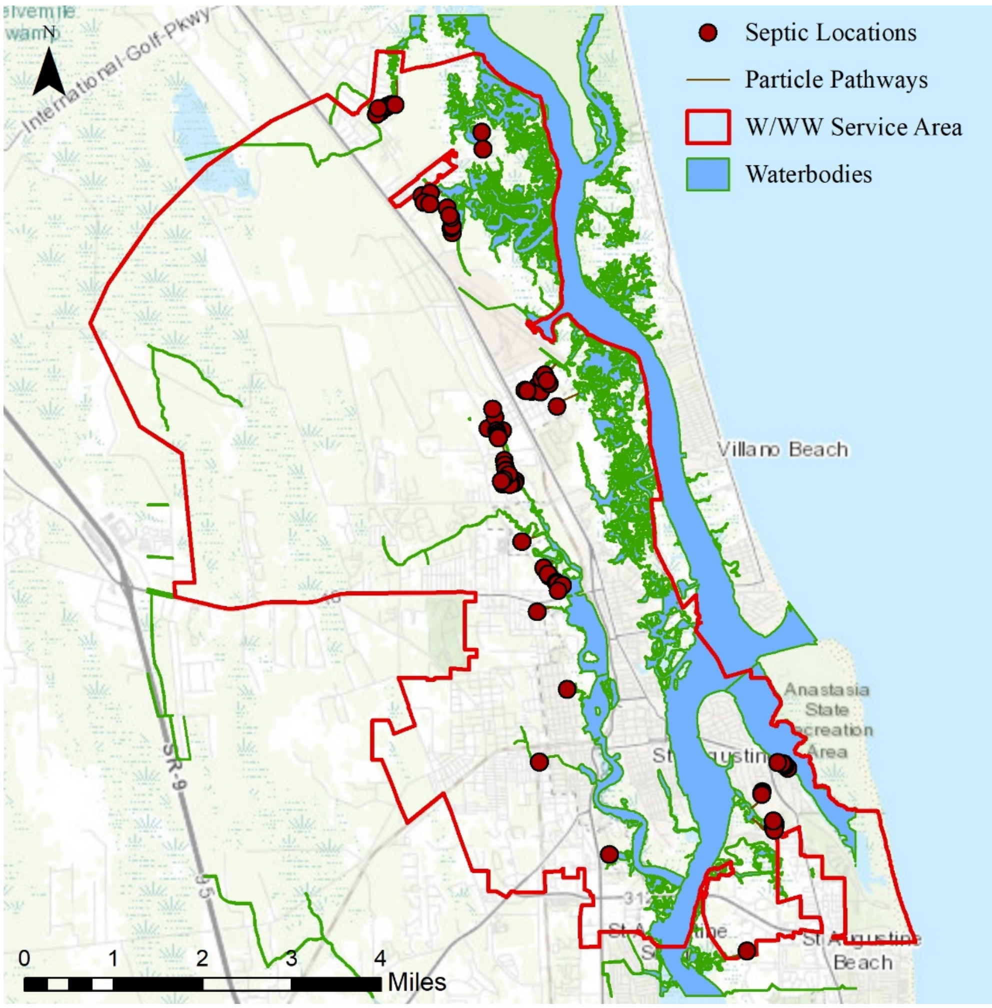

Figure 4.5 OSTDS locations and particle pathways for OSTDS at risk of increased flooding

4.7.OSTDS at risk for Storm Surge

Table 4.7 ArcNLET modeling estimates for OSTDS at risk of storm surge

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
5	3	100.26
7	2	42.38
13	1	10.24

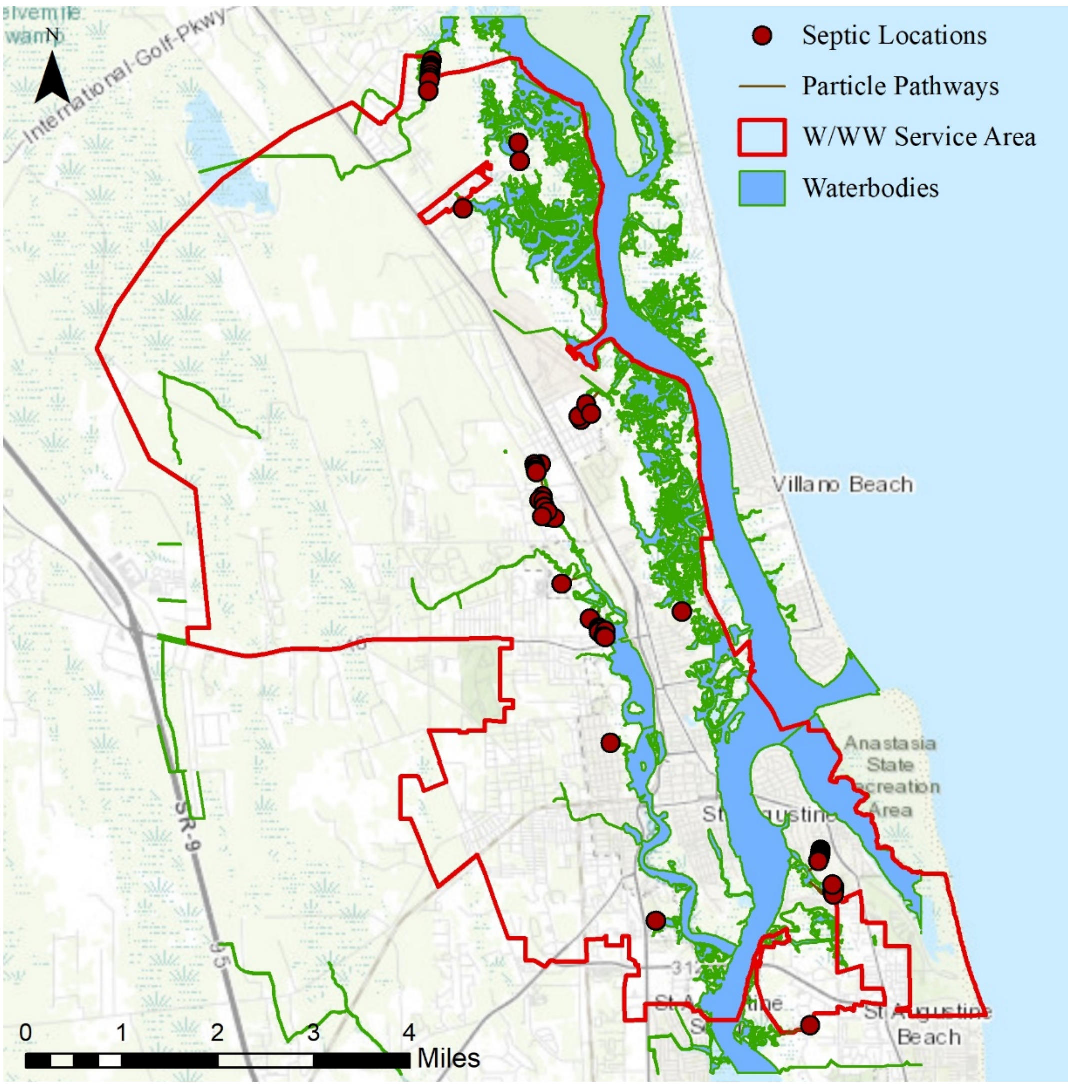

Figure 4.6 OSTDS locations and particle pathways for OSTDS at risk of storm surge

4.8.OSTDS with severely limited soils

Table 4.8 ArcNLET modeling estimates for OSTDS with severely limited soils

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
12	38	460.31
5	4	114.86
2	11	90.01
7	2	42.38
4	3	33.51
10	1	19.54
13	2	16.78

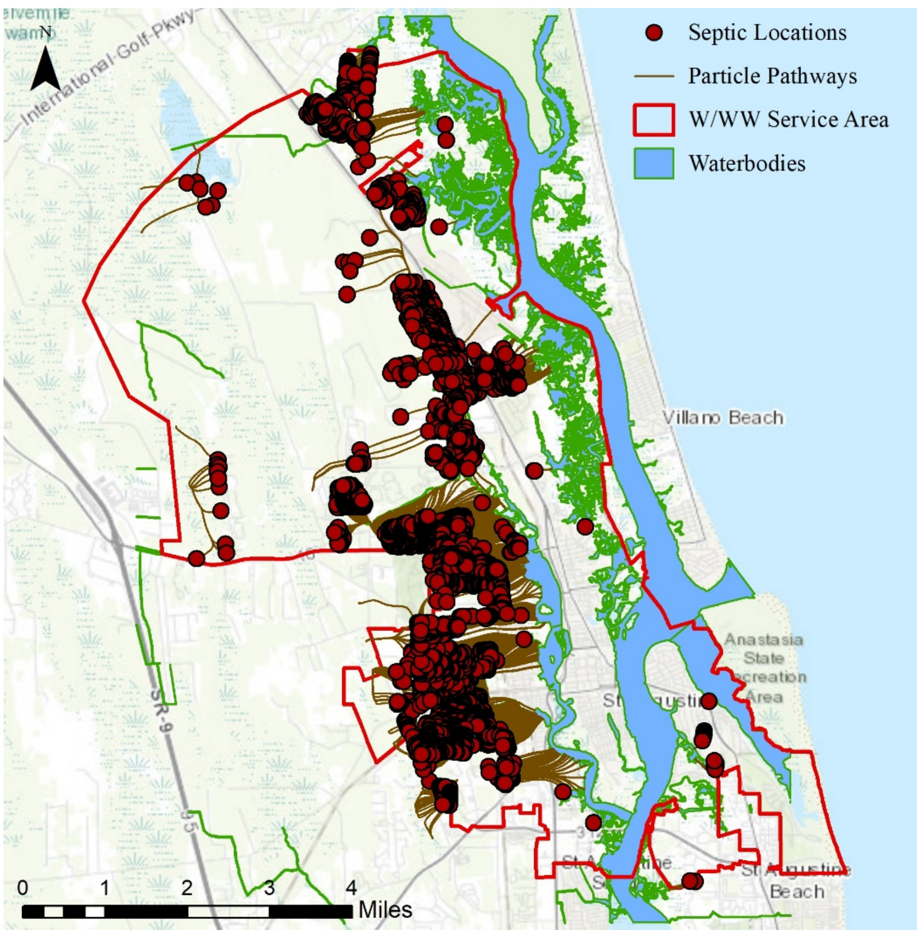

Figure 4.7 OSTDS locations and particle pathways for OSTDS with severely limited soils

4.9.Non-homesteaded parcels with OSTDS

Table 4.9 ArcNLET modeling estimates for OSTDS with no homestead exemption

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
10	24	571.49
2	17	225.99
12	12	128.34
8	7	51.67
7	1	19.29
4	2	15.08

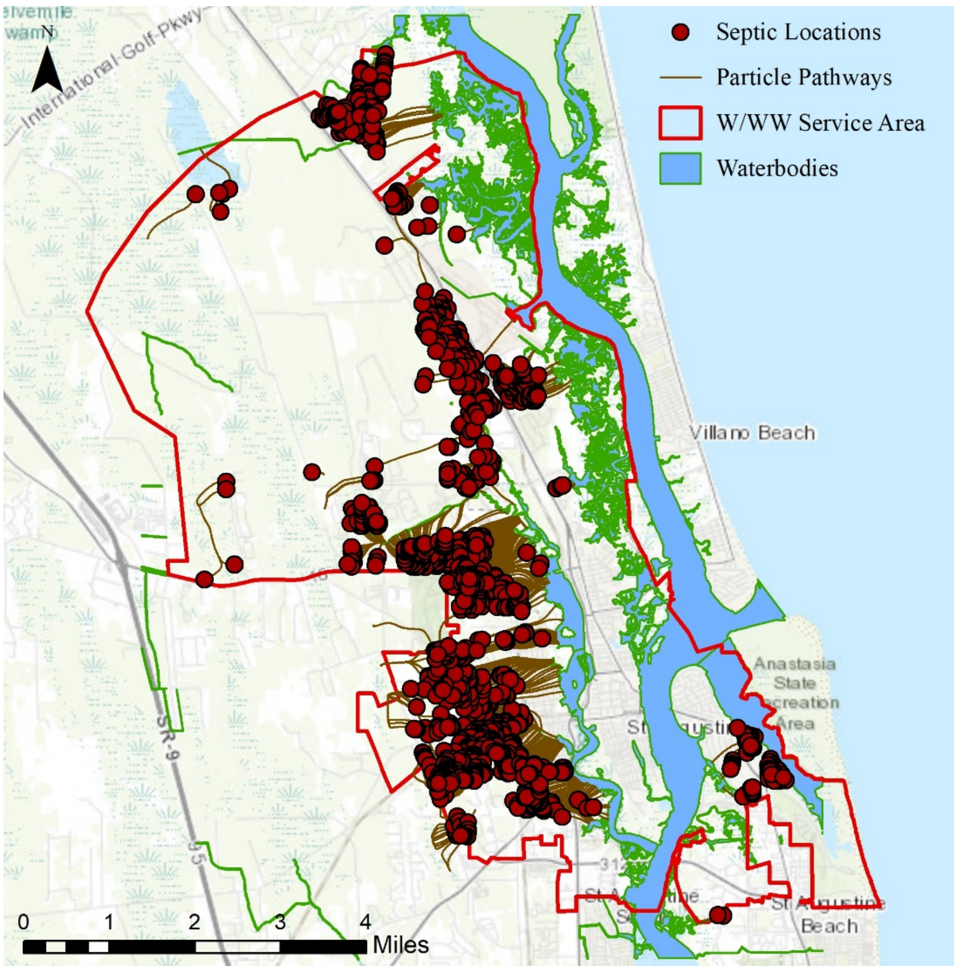

Figure 4.8 OSTDS locations and particle pathways for OSTDS with no homestead exemption

4.10. Non-homesteaded parcels with OSTDS within the 1-foot SLR scenario

Table 4.10 ArcNLET modeling estimates for non-homesteaded parcels with OSTDS within the 1-ft SLR scenario

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
5	0	0
12	0	0

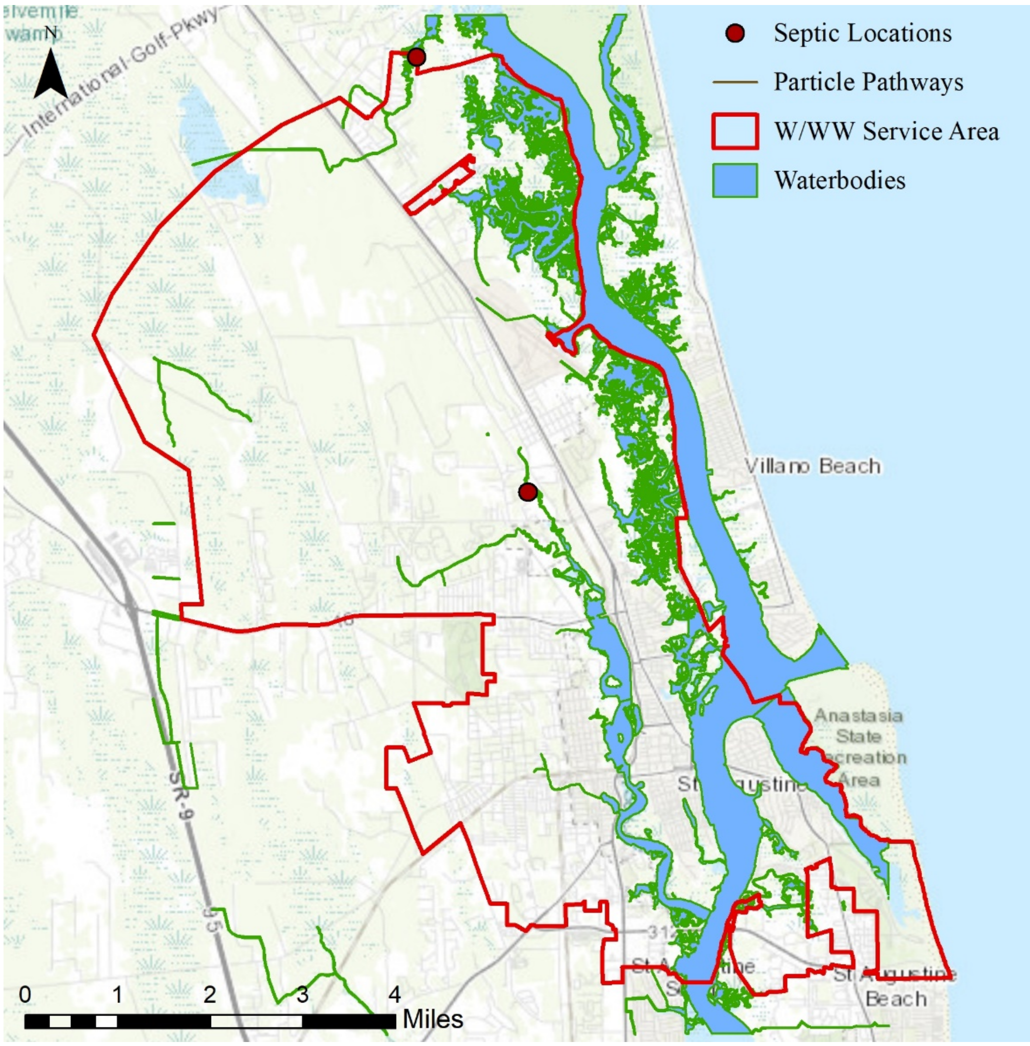

Figure 4.9 OSTDS locations and particle pathways for non-homesteaded parcels with OSTDS within the 1-ft SLR scenario

4.11. Non-homesteaded parcels with OSTDS within the 2-foot SLR scenario

Table 4.11 ArcNLET modeling estimates for non-homsteaded parcels with OSTDS within the 2-ft SLR scenario

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
5	0	0
11	0	0
12	0	0

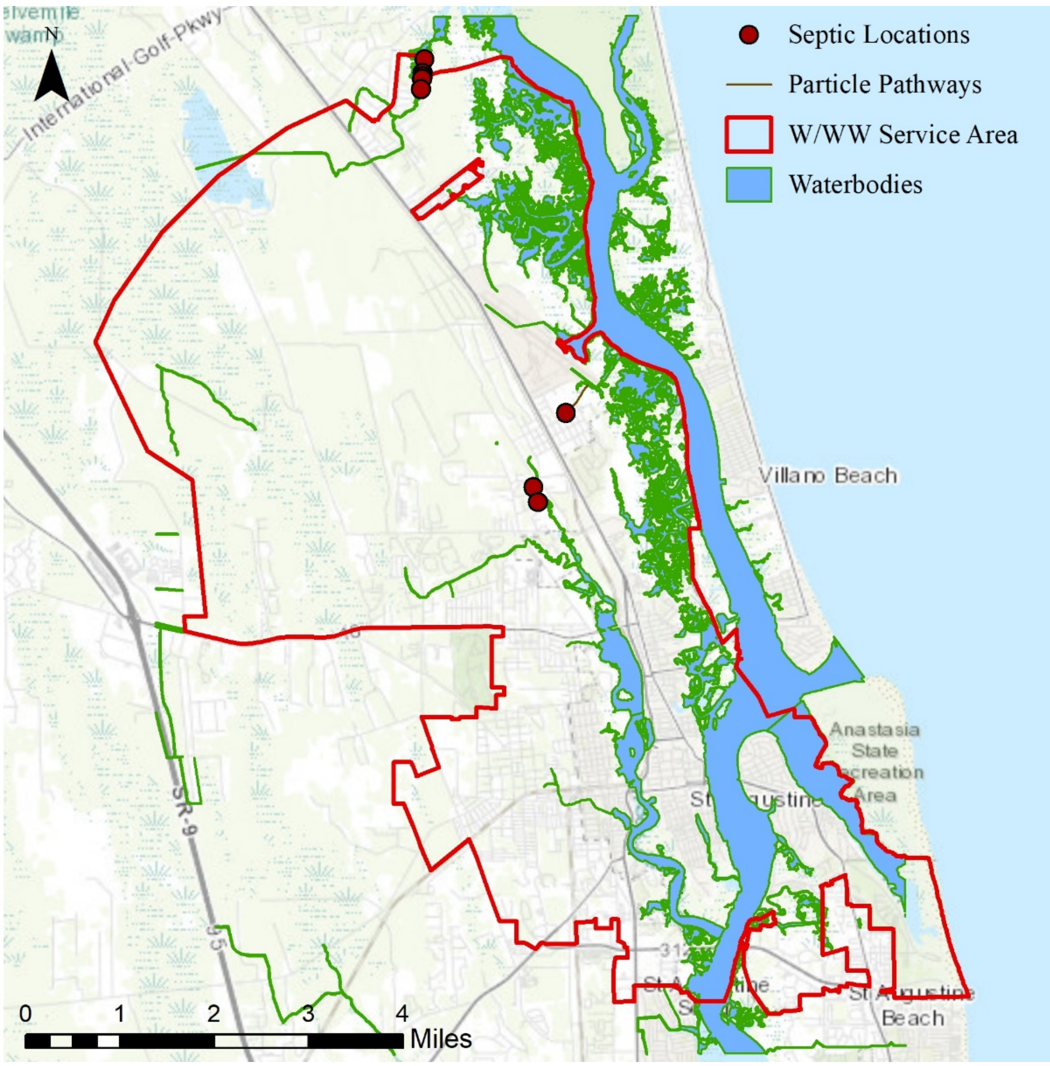

Figure 4.10 OSTDS locations and particle pathways for non-homesteaded parcels with OSTDS within the 2-ft SLR scenario

4.12. Non-homesteaded parcels with OSTDS within the 3-foot SLR scenario

Table 4.12 ArcNLET modeling estimates for non-homesteaded parcels with OSTDS within the 3-ft SLR scenario

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
7	1	19.29

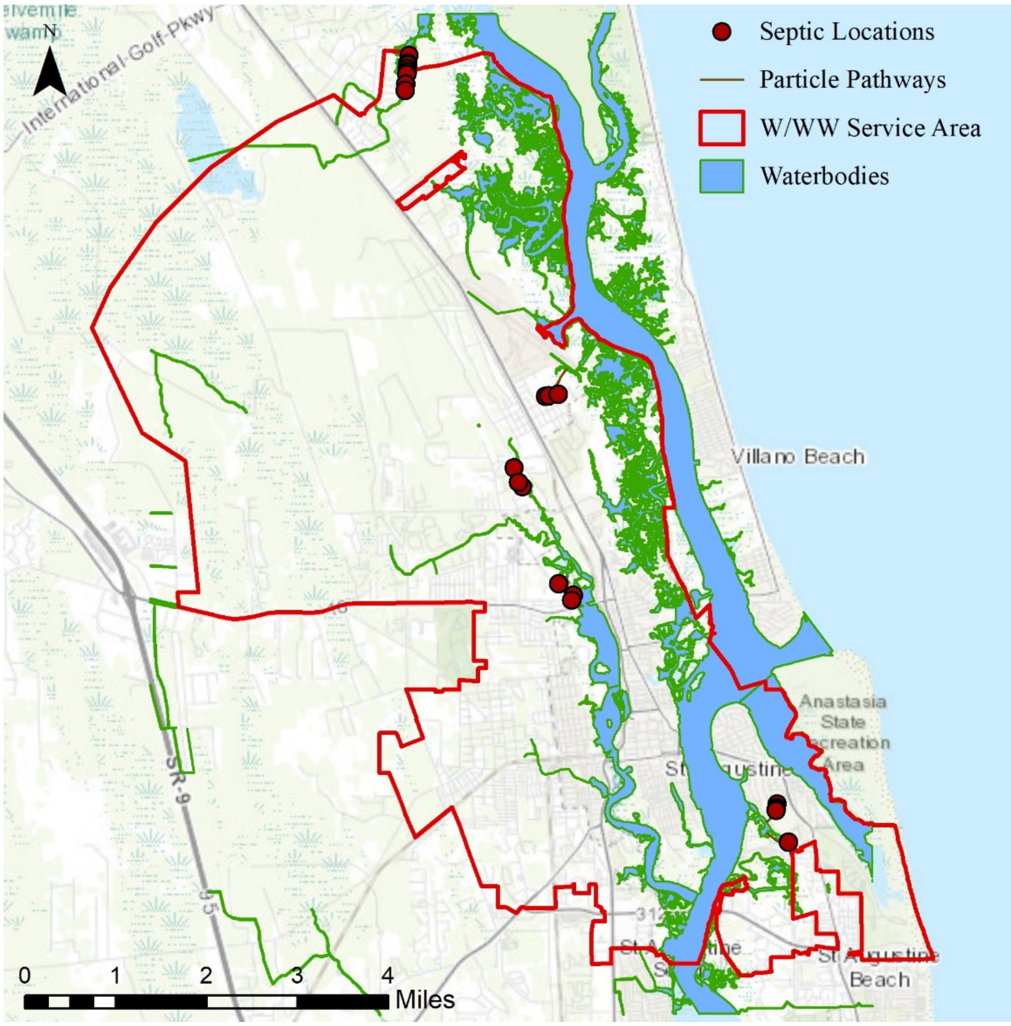

Figure 4.11 OSTDS locations and particle pathways for non-homesteaded parcels with OSTDS within the 3-ft SLR scenario

4.13. Non-homesteaded parcels with OSTDS vulnerable to HTF Flooding

Table 4.13 ArcNLET modeling estimates for non-homesteaded parcels with OSTDS at risk of increased flooding

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
10	1	120.28
12	2	24.68

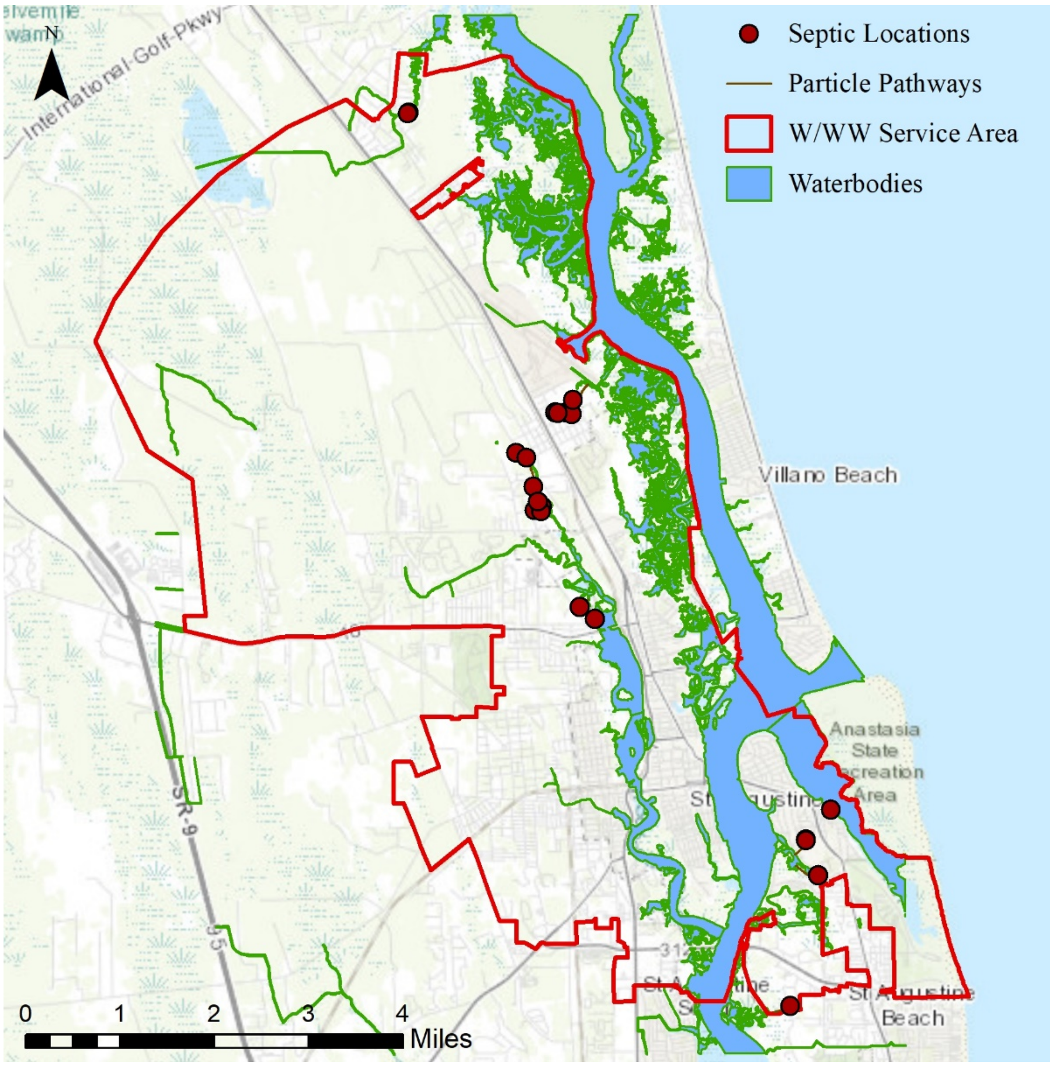

Figure 4.12 OSTDS locations and particle pathways for non-homesteaded parcels with OSTDS at risk of increased flooding

4.14. Non-homesteaded parcels with OSTDS vulnerable to Storm Surge

Table 4.14 ArcNLET modeling estimates for non-homesteaded parcels with OSTDS at risk of storm surge

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
7	1	19.29

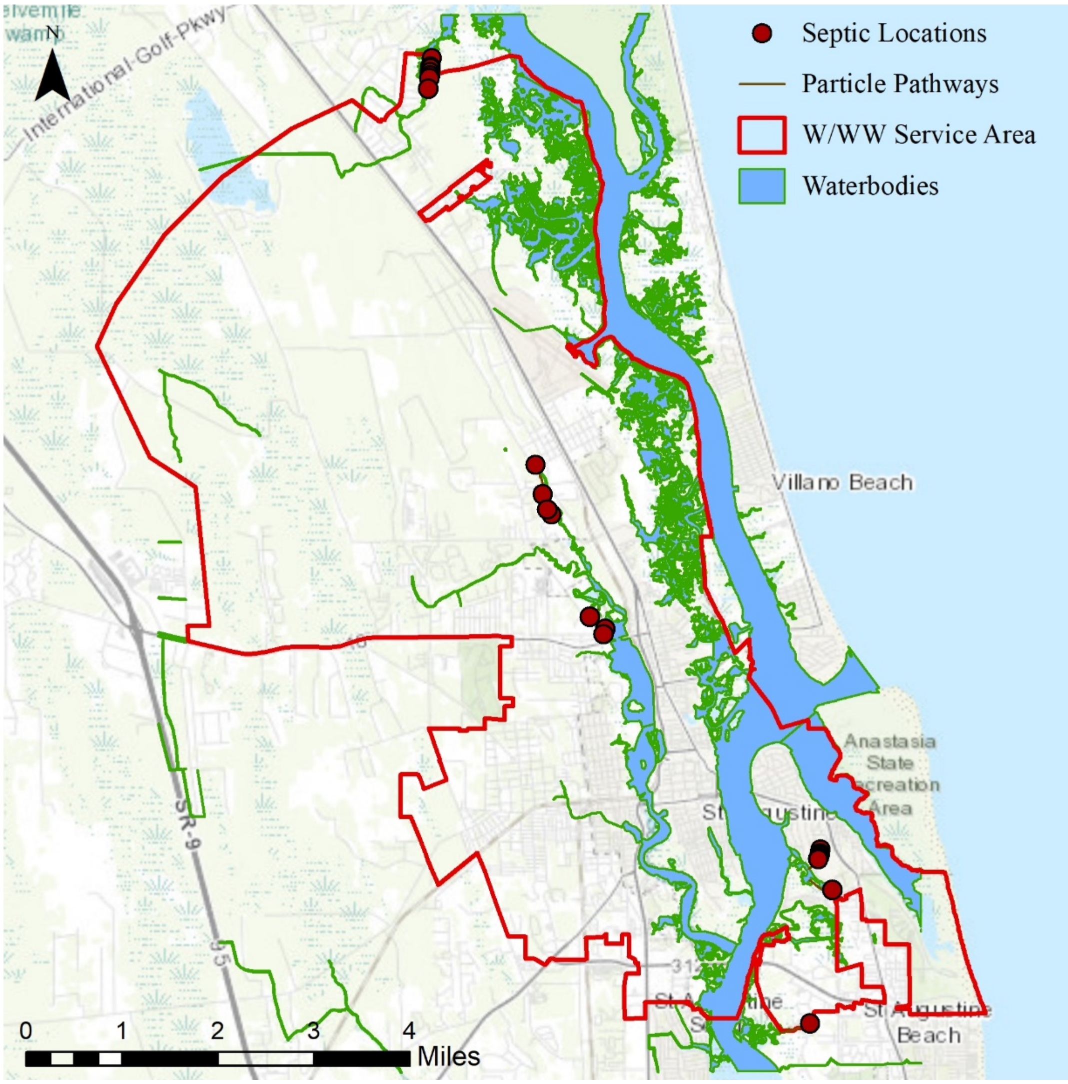

Figure 4.13 OSTDS locations and particle pathways for non-homesteaded parcels with OSTDS at risk of storm surge

4.15. Non-homesteaded parcels with OSTDS with severely limited soils

Table 4.15 ArcNLET modeling estimates for non-homesteaded parcels with OSTDS with severely limited soils

Waterbody ID	OSTDS Plumes to Reach Waterbody	Mass Output Load (lbs/yr)
12	7	82.54
2	7	57.23
10	1	19.54
7	1	19.29
4	1	8.51

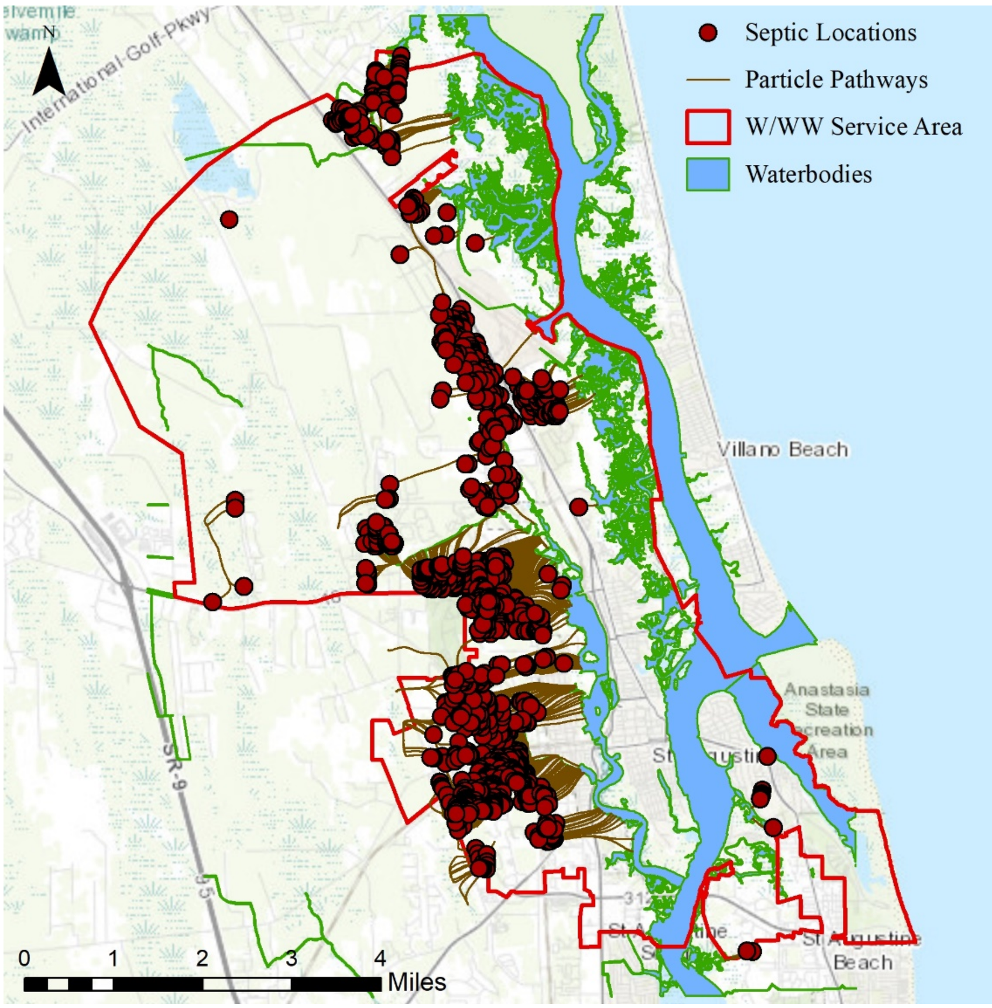

Figure 4.14 OSTDS locations and particle pathways for non-homesteaded parcels with OSTDS with severely limited soils

Per Table 4.2 and Figure 4.1, septic systems in Salt Run are estimated to contribute the highest loading in the study area with 46 of the 78 systems providing 1,291 lbs N/yr. This load is more than twice the second highest load which is at Stokes Creek with 51 of the 239 systems contributing 593 lbs N/yr. This dramatic difference in loading with close to the same number of contributing systems can be considered from several parameters. Most of the systems in Salt Run are in only slightly limited soils whereas most of the systems in Stokes Creek are in severely limited soils, characteristics that are partially reflected in the hydraulic conductivity and porosity layers used as inputs to ArcNLET. Also, particle paths for systems in the Stokes Creek area are longer and travel through a swampy/marshy area where much of the nutrients can be attenuated before reaching surface waters.

Even though Salt Run has the highest estimated nitrogen loading in this study set, the amount is not high enough to result in algal blooms or nitrification. For perspective, The City Manager noted in the April 26, 2021 City Commission meeting, that the cumulative estimated loads for all these waterbodies is approximately 2% of the load released from the wastewater treatment plant and the estimated loads to Salt Run are approximately 1% of the load released from the wastewater treatment plant (CoSA 2021). So even though Salt Run has the highest estimated nitrogen exports it is not creating a problem such as algal blooms or eutrophication. This may also be assisted by the hydrodynamics of the waterbody. It is directly adjacent to the St. Augustine Inlet and would experience a lot of mixing in this tidal waterbody.

There are 40 systems in Salt Run that have no homestead exemption which may indicate short term rental use. Twenty-four of these systems contribute 572 lbs N/yr based on the ArcNLET estimates which are based on normal occupancy conditions. In Stokes Creek there are 80 non-homesteaded parcels with only 13 systems contributing 128 lbs N/yr.

In addition to non-homesteaded parcels, ArcNLET estimates were modeled for 1-,2- and 3-foot sea level rise, high tide flooding potential, storm surge potential and systems in severely limited soils. Another subset was planned for parcels experiencing rising groundwater levels but since all parcels are experiencing this one can refer to the 'All OSTDS in the study area' results. Each of these estimates were re-modeled for all non-homesteaded parcels as well. These subsets can provide useful information for municipal and agency staff seeking to understand the demographics of risk to septic systems in their area. For example, it may be necessary to prioritize an area with near term groundwater rise inundation with lower loading outputs over an area with a longer horizon sea level inundation and higher outputs, because although the groundwater risked systems have lower outputs, they have a greater risk of near term inundation that could release raw outputs to the surface. Additionally, where new developments are being built, especially when this is increasing density near areas with high loading outputs, planners may be able to prevent new septic systems from being installed in these locations.

4.16. Calibration and Sensitivity Modeling

Developers of the ArcNLET tool have provided methods for calibrating the model to better estimate loading outputs. This requires data of groundwater nitrate levels though, which are not often available. Data were requested from FDEP and SJRWMD from groundwater monitoring activities but these did not include any form of nitrogen monitoring. Because groundwater nitrogen levels were not available, we were not able to develop calibrated results. This is unfortunately common for ArcNLET users in Florida since there is not a long history of monitoring groundwater for biological data.

This however does not render these estimates unusable. These estimates are still reasonable enough to be used as a supplement to the vulnerability assessment scores in that they can tell use relatively how much nitrogen might be reaching area waterbodies from septic systems that have high vulnerability scores. In this way they can still be used to prioritize an area of high vulnerability scores and high estimated nitrogen exports, over an area of high vulnerability scores and low estimated nitrogen exports.

In lieu of calibrating the model with groundwater nitrogen observations, we performed a sensitivity analysis using just septic systems in Salt Run because they have the highest estimated loading. We found that using default settings and changing concentration levels (C0=30, 40 and 60) resulted in no change in loading estimates. Instead, setting a specified z (vertical plume distance in meters), or leaving Min (M-in or Mass in) at default 20,000 and setting Zmax (maximum vertical plume distance calculated in meters) leads to different outputs. Z represents the vertical plume difference and Zmax represents the maximum vertical distance at which the plume could grow before reaching a confining layer (clay, groundwater level). The groundwater elevation calculated using the linear model for the septic systems in Salt Run ranges from 1.3 m to 4.2 m with a median of 3.5 m and a mean of 2.2 m. Using the median and mean for z, and median and max for Zmax resulted in the estimates seen in Table 4.16.

Test Setting	Mass Output Load (lbs/yr)
z = 3.5 (median of groundwater elevation)	2,306.45
z = 2.2 (mean of groundwater elevation)	1,449.63
Zmax = 3.5 (median of groundwater elevation)	1,624.04
Zmax = 4.2 (max of groundwater elevation)	1,353.77

Table 4.16 Results of Sensitivity Analysis.

4.17. Travel time from source to waterbody

The ‘Particle Pathways” layer includes values for the ‘travel time’ in days for nutrients to travel from the source septic system to the receiving waterbody. The particle pathways are calculated for all source locations regardless of whether or not the nutrient plume is estimated to reach the waterbody. This table also provides the plume length and allows for identification of those plumes that do not reach the waterbody (plume length is less than path length). Using plume length and path length to identify where plume length is greater than or equal to path length, we divided the travel time (given in days) by 365 to convert to years (Effluent travel time in years = the value in the Plume info file, field name ‘pathTime’ which is in days, divided by 365). This identifies 150 septic systems with nutrient exports reaching receiving waterbodies. The travel time for these locations ranges from 4 months to almost 8 years with an average travel time of 4 years (Figure 4.15). This information can help staff identify and prioritize areas for action. For example, when allocating scarce resources between two areas of equal distance from existing infrastructure, an area with shorter travel times may be prioritized to prevent those inputs to receiving waterbodies.

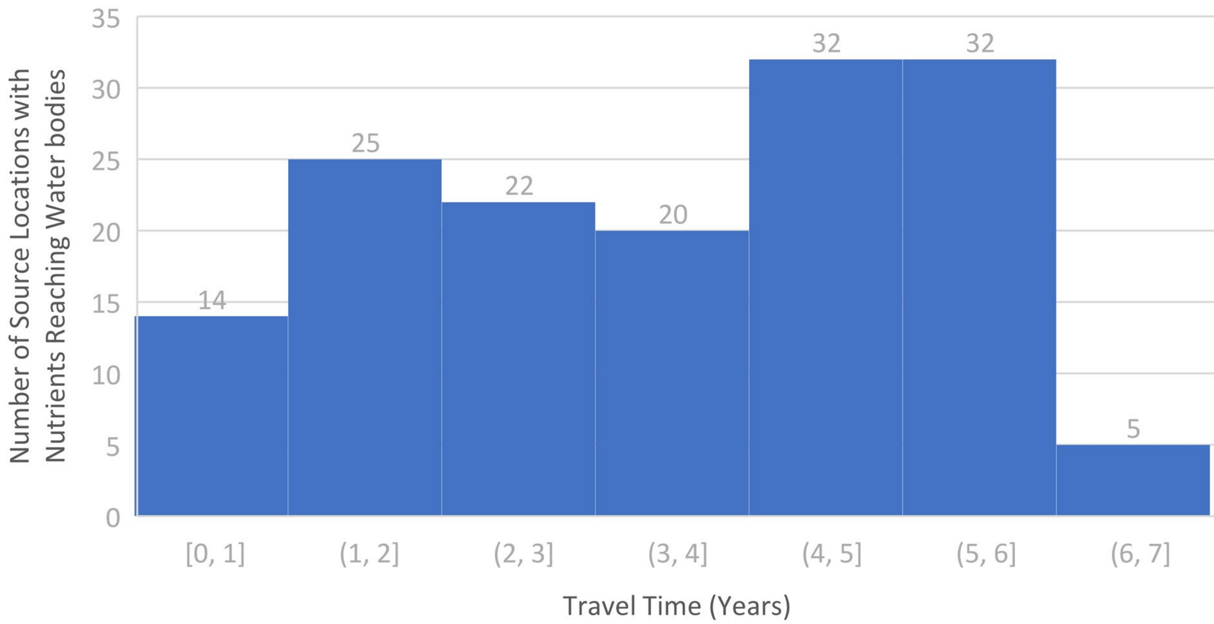

Figure 4.15 Number of source locations with nutrients reaching waterbodies and travel time in years.

5. Study Limitations and Options

There are some generalized limitations of this study based on the inputs and how they were processed. These include publicly available data gathered from NOAA, the USDA and the USGS. Data used from NOAA included sea level rise estimates, high tide flooding and storm surge data. The process of data development was necessarily a combination of regional and local data, additionally this data is a few years old. This means the values available from these datasets may not be as accurate as locally calculated estimates. Estimates of these values could be improved if local modeling of sea level rise, high tide flooding and storm surge were calculated. Locally derived estimates are also more time consuming. Data collected from the USDA includes hydraulic conductivity, porosity and sanitary soils designations. Similar to NOAA data, these data will be derived based on findings of similar characteristics in other locations. One way this can be readily seen is by looking at the sanitary soil designations in Salt Run. Of the 78 septic systems in salt run 1 falls within a severely limited soil designation while the other 77 fall within slightly limited soils designation. Practical understanding recognizes that it is highly unlikely there is a hard divide in soil types from one parcel to its. The same is true for hydraulic conductivity and porosity, these data begin as polygon layers with distinct edges from one polygon to the next, representing a change from one value to the next, which is also not something that happens in real life. Here too, to get better quality inputs would require field work and sampling to collect the actual values of the soil characteristics.

5.1. Vulnerability Assessment

The vulnerability assessment parameters, ranks and weights used in this project are specific to the threats facing septic systems in the St. Augustine study area. Another municipality may feel that there are other parameters more relevant to the climate change related risks that septic systems face in their area and this should be discussed with the staff in that location so that the most effective vulnerability assessment parameters, ranks and weights can be determined for the assessment. Some additional parameters to consider might include the distance to existing sewer infrastructure. Shorter distances could be assigned higher ranks which would increase their vulnerability assessment score which could result in a higher priority for a septic to sewer conversion project. Another parameter to consider might be the estimated nitrate loading to nearby waterbodies. This might be accomplished by assigning septic systems that have plumes that reach waterbodies with a high rank and plumes that do not reach the waterbody with a low rank.

5.2. ArcNLET

ArcNLET is likely to present the greatest limitation for several reasons. It requires a large investment of time to adequately edit the DEM and waterbody data to create the best input layers. Ye discusses how to edit the DEM in both the User's Manual and the Application manual, which is useful, but there is a lot of manual work to identify where areas of the DEM (roads and bridges that create artificial barriers to water flow) need to be modified. Waterbody data can also be time consuming to create accurately. Data available from NHD must be reviewed against known waterbodies and may have to be edited, added or deleted to get an accurate waterbody layer.

As mentioned previously, a significant limitation to ArcNLET estimates is whether or not the model was calibrated. Calibration is best done using historical data of nitrogen monitoring in groundwater. Using this data, input setting values can be adjusted until output estimates approximate historical data values. Unfortunately, nitrogen monitoring in groundwater has not been regularly collected so this level of calibration can not be achieved. Another way to reasonably calibrate the ArcNLET estimates is using surface water nitrogen monitoring data. This too would still require time to adjust input settings until achieving estimates that approximate the historical values. However as discussed previously, uncalibrated estimates should not be completely disregarded for use in this project. They still provide a reasonable estimate of values relative to the septic systems and waterbodies and so can be useful for identifying areas of higher nitrogen loading vs lower nitrogen loading. It should also be noted that this modeling assumes all septic systems are operating efficiently, are not leaking and are not in need of repair or maintenance and are therefore not exporting higher than expected NH_4 or NO_3 to soils and/or groundwater and eventually surface waters.

5.3. Supporting data to request from the municipality

For this project we received wastewater infrastructure data from city staff and this was used in the early steps of developing the septic system source locations. We were able to use this to step through which of the FDOH identified septic systems had been converted to municipal sewer already or which were still existing systems. It was also critical to review the edited septic system source locations with city staff to identify any converted septic systems that were not identified from the infrastructure data.

6. CONCLUSION

While there has been some early research to understand how climate change impacts may affect septic systems, it has not provided a comprehensive understanding of these impacts. Early work has looked at the change in groundwater levels relative to drainfields and shows that this vertical separation distance is decreasing. Other research has looked at possible water inundation due to strong storms and hurricanes, and one has even looked at how the change in soil temperature and moisture affects how the primary pollutants change. Until this project there has not been research that looked at the impact of multiple threats to septic systems and quantified the risk multiple threats present to septic systems. This project introduces new research to assess the vulnerability of septic systems to multiple threats and estimates the amount of nitrogen exported to surface waterbodies by these septic systems. The multi-criteria weighted vulnerability assessment provides a method of quantifying risks to septic systems from multiple climate change related threats and provides municipalities with an understanding of where their most at risk septic systems are located. Additionally, this project used ArcNLET to estimate nitrogen exports from these at-risk systems to area waterbodies. This information shows where septic systems are contributing relatively higher nitrogen exports than other systems and provides additional information such as the travel time of exports. Nitrogen export estimates can also help municipalities identify where higher loading septic systems are located. Using these two pieces of information together provides municipalities with valuable information about how many septic systems are in their jurisdiction, where the most -at risk septic systems are located, and where their highest loading septic systems are located. Using these information together can help municipalities prioritize projects for action to reduce risk and exports, provide valuable information about the demographics of septic systems in their area, provide this information to homeowners and residents potentially affected by the outcomes, and provides valuable supporting documentation for funding applications for projects aimed at resolving these issues.

The risks to septic systems have been quantified via a multi-criteria vulnerability assessment developed with the input of City of St. Augustine staff. Staff selected 4 variables from a variety of parameters and a weighting option for those parameters. Using the values staff identified, vulnerability assessment scoring was calculated for all septic systems. Additionally, the average vulnerability score by subdivision was calculated, and the number of septic systems per subdivision and density per acre were calculated. ArcNLET was used to estimate nitrate loading to surface waters from all single family residential septic systems in the City's water/wastewater service area and multiple subsets of the full set.

In this project we identified 2,938 residential septic systems in the St. Augustine water/wastewater service area. Systems that were at risk for sea level rise, high tide flooding, storm surge, rising groundwater levels and having unsuitable soils for effluent processing were given a vulnerability assessment score based upon parameters and weights identified by city of St. Augustine staff. These scores were used in a Hot Spot analysis to identify areas of statistically significant clustering of high scores, indicating areas of concern for climate change impacts. Additionally, ArcNLET modeling was performed to estimate nitrogen loading from these systems to area waterbodies. Subsets of the full dataset were developed to highlight loading estimates for areas with specific risks. ArcNLET is often used to estimate nitrogen loading for areas that are considering septic enhancement or conversion projects. In this project the loading estimates were useful for prioritizing areas of high input for such projects, but also provided useful information about travel times of nitrogen plumes which can also help prioritize projects with near term travel times. The rate of rise in groundwater levels was also helpful for prioritizing projects that might experience inundation sooner than other areas.

Vulnerability assessment results indicate that septic systems in Stokes Creek, near the airport, and in the north reaches of San Sebastian River have high risk of vulnerability to climate change related impacts. These areas, plus areas in West Augustine and Salt Run also experience loading from septic systems as indicated by the results of the ArcNLET modeling outputs for all OSTDS in the study area (Table 6.2 and Figure 6.1). In fact, ArcNLET modeling outputs indicate that there is significant nitrate loading to area waterbodies, especially Salt Run and Stokes Creek. These two waterbodies often appeared to have the highest loading in many of the subsets modeled. But while they have high nutrient exports, systems in Salt Run do not appear to be at a high risk of climate change impact as their vulnerability assessment scores were low, placing them in a cold spot with a 99% confidence level.

This presents key information for area stakeholders trying to prioritize areas to improve the resiliency of their communities through wastewater treatment upgrades. The Stokes Creek area has both high vulnerability scores and high nutrient inputs. Salt Run has high nutrient inputs but low vulnerability scores. Another area that has been of concern to city staff is the Oyster Creek and lower San Sebastian areas, also known as West Augustine. This area has approximately 1,300 septic systems and has been motivated for several years now to make septic to sewer upgrades and has applied for several funding opportunities to complete these projects. This area does show a high level of nutrient loading but, like Salt Run, has a high confidence level of low vulnerability. Getting stakeholder buy in for septic to sewer conversion projects is often difficult and takes time. Since residents in this area are already motivated to pursue septic to sewer projects it would not be recommended to abandon these projects in this area. But it would also be advisable to begin to develop motivation in the Stokes Creek area since that area has high vulnerability and high nutrient loading, and then follow up with similar actions in the Salt Run area. Using the two methods, Vulnerability Assessment and ArcNLET modeling, together provides greater insight into the risks and impacts of septic systems in a particular area, making project identification and prioritization easier for the relevant agencies.

The vulnerability assessment developed in this project is a new method to identify septic systems at risk of climate change related impacts in low lying coastal communities. Pairing this with ArcNLET nitrogen estimates is also a new practice. Each of these methods alone can provide communities with useful information about the status of septic systems in their area, but coupling these together creates a powerful tool to help communities identify which areas are at high risk vs low risk, and where nitrogen exports might be higher or lower for those same areas. Using the vulnerability assessment with the ArcNLET modeling can show communities if there are areas of high vulnerability and high exports, which should be prioritized for resiliency actions, vs areas of low vulnerability and low exports which can be addressed after the more critical areas.

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8. APPENDIX A – WASTEWATER TECHNOLOGIES REPORT

(see next page)