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Policy Analysis

Assessing the Socio-Environmental Risk of Onsite Wastewater Treatment Systems to Inform Management Decisions

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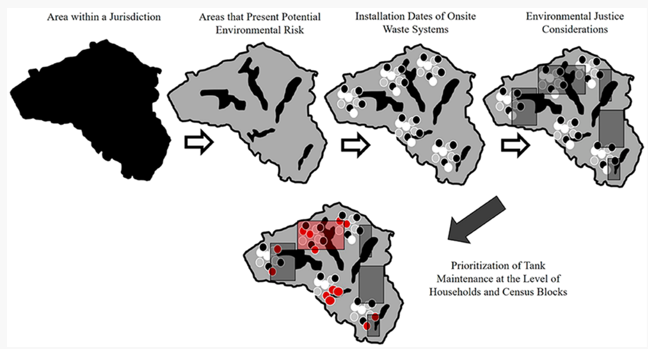
ABSTRACT: Quantifying the risk that failing onsite waste treatment systems (OWTS), such as septic systems, present to human health and the environment is a key component in natural resource management. We integrated environmental and socio-demographic data to assess the potential environmental risk and environmental justice concerns related to septic infrastructure. We used this process to develop a framework that can be applied in other jurisdictions. We found only 8% of the registered OWTS presented potential environmental risk due to the topographic, hydrologic, or edaphic characteristics of their placement. In contrast, almost 70% of the OWTS presented potential environmental risk due to their age (25 years or older). Approximately 60% of the OWTS we estimated to be at risk from age or placement were found in census blocks with more than 30% of the population living below the poverty line, had a population that was more than 50% nonwhite, or was predominantly nonwhite and impoverished. Our work suggests that jurisdictions with limited information about septic infrastructure may be able to use geospatial data that they do have to predict the parcel-level locations of OWTS. These locations can then be used to inform environmental monitoring to proactively address environmental justice concerns.



■ INTRODUCTION

The identification and mitigation of sources of pollution associated with aging and obsolete wastewater treatment infrastructure is a management challenge faced by governments throughout the world.[1,2] The traditional approach to address surface water pollution is to focus on point sources, such as wastewater treatment plants, and reduce the volume and regulate the permitted constituents in discharge from point sources. Yet, for a number of pollutants, diffuse sources, such as agriculture and urban runoff, abandoned mines, and other types of poorly performing wastewater treatment infrastructure (WWTI), are having increasingly important contributions to violations of water quality standards.[3,4] Onsite wastewater treatment systems (OWTS), such as septic systems, are an essential component of wastewater treatment infrastructure throughout the globe.[5−7] When septic systems function properly, they can remove large proportions of pollutants common in surface waters, such as phosphorus, from wastewater.[8,9] However, research continues to demonstrate the adverse impacts poorly functioning septic systems can have on water quality at smaller spatial scales.[4]

The distribution and density of septic systems are increasing in many regions of the world.[1,10] For example, in the United States (US), septic systems serve between 20 and 25% of houses, including half of mobile homes,[11,12] and more than 30% of new homes being constructed are on septic.[10] Collectively, onsite systems in the US treat more than 4 billion gallons of sewage daily.[13] Though often thought to be relegated to rural areas, as human populations have grown and development patterns have changed, a large proportion of septic expansion occurs in urbanizing areas.[10,14] In rapidly expanding urban centers, such as the greater Atlanta metropolitan region in the southeastern US, the extension of aboveground infrastructure may not always coincide with an expansion of sewer systems. Septic sheds can be nested within sewer sheds, and unexpectedly large proportions of metropolitan waste may be treated by onsite systems.[15] Additionally, alternative onsite systems are becoming more common in areas with high water tables or soils unsuitable for conventional septic drain fields and for enhanced nutrient removal.[10] Thus, municipal wastewater infrastructure is typically a heterogeneous mixture of publicly and privately managed aging technology.

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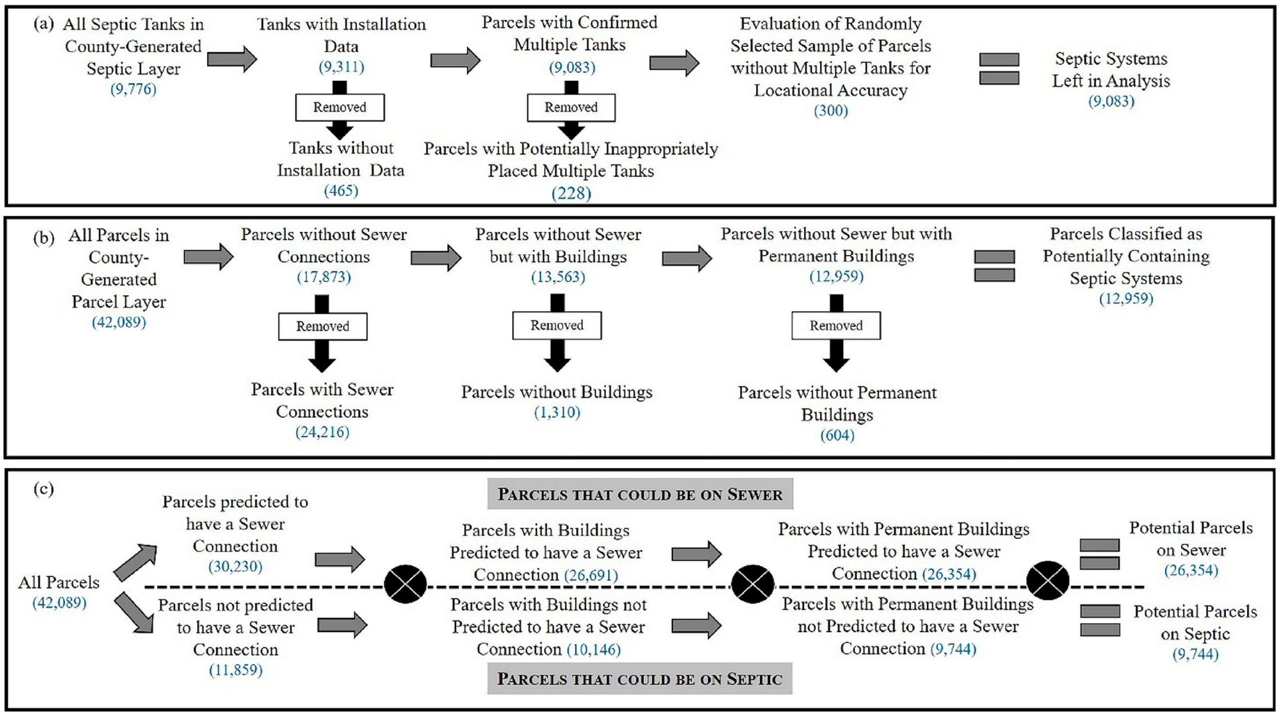

Figure 1. Conceptual diagrams of the processes used to evaluate existing data sets and to generate new septic data. (a) Methods used to evaluate the known locations of septic systems in the county. (b) Approach used to evaluate the number of parcels containing septic systems that may not be registered with the county using geocoded data of sewer connections. (c) Procedure that can be applied to evaluate the number of parcels that may have septic systems within a jurisdiction without access to geocoded information about sewer connections. The numbers in blue are the number of OWTS from our data set.

Local governments are often challenged to manage the impacts of complex networks of aging and obsolete septic systems on human health and the environment with very limited data to inform their decisions. Unlike sewerage, which is often monitored and maintained by local governments in perpetuity, onsite waste systems are typically managed by individual landowners after they are installed and municipal intervention by public health officials only occurs when system failure presents a risk to the community.[16] Integrated networks of communication between public health officials and water resource managers can be limited; hence, many local governments do not have the information needed to assess how the location and condition of septic infrastructure may threaten the integrity of surface waters.

Managing decentralized systems is a complex process that requires the development and implementation of public outreach, education, and participation programs; municipal planning; and training to enable officials to assess the design, construction, and performance of OWTS operation and maintenance.[17] Globally, very little data are available on the average age or maintenance records of septic systems.[1,2] The average lifespan of a septic system is between 15 and 40 years, but this time period is strongly influenced by the volume and constituents of waste and maintenance of the system.[18] At the turn of the century, estimates from the US Census Bureau indicated approximately half of the homes served by onsite systems were more than 30 years old.[10] Failure rates are expected to increase with system age; hence, declining surface water quality associated with high densities of aging septic systems may be a challenge faced increasingly by communities throughout the US. Studies have suggested that approximately half of OWTS owners do not maintain their OWTS according to recommended guidelines.[19,20] Collectively, this information suggests that high densities of aging and poorly monitored septic systems may compromise the integrity of freshwater systems throughout the US.

To address some of these concerns, the US Environmental Protection Association (EPA) developed management guidelines to encourage the institutionalization of OWTS management; enhance the quality of state, tribal, and local management programs; and outline guidelines for minimum levels of management, monitoring, and educational activities.[17] The guidelines are a collection of five management models that reflect the need for enhanced oversight and improved management practices as potential risks to public health and the environment and the complexity of treatment systems increase. Included in each model is the need to inventory existing systems and assess their level of performance.[17] Therefore, in every community that relies on OWTS, detailed information is needed about the number and condition of septic resources and new tools are required to support local governments in generating forward-thinking policies to guide the collective management of OWTS.

Demographic characteristics of a population, such as income level and race, are often correlated with the condition of wastewater infrastructure within a jurisdiction,[21−26] and many communities are concerned about the environmental justice implications of decisions related to wastewater infrastructure.[27−29] The cost of system maintenance (e.g., pumping: ~$200−500 USD) or replacement (i.e., thousands to tens of thousands of USD) can be prohibitive for many homeowners, especially in impoverished communities.[30] This suggests that communities striving to address environmental justice concerns need to consider potential interactions between the quality and

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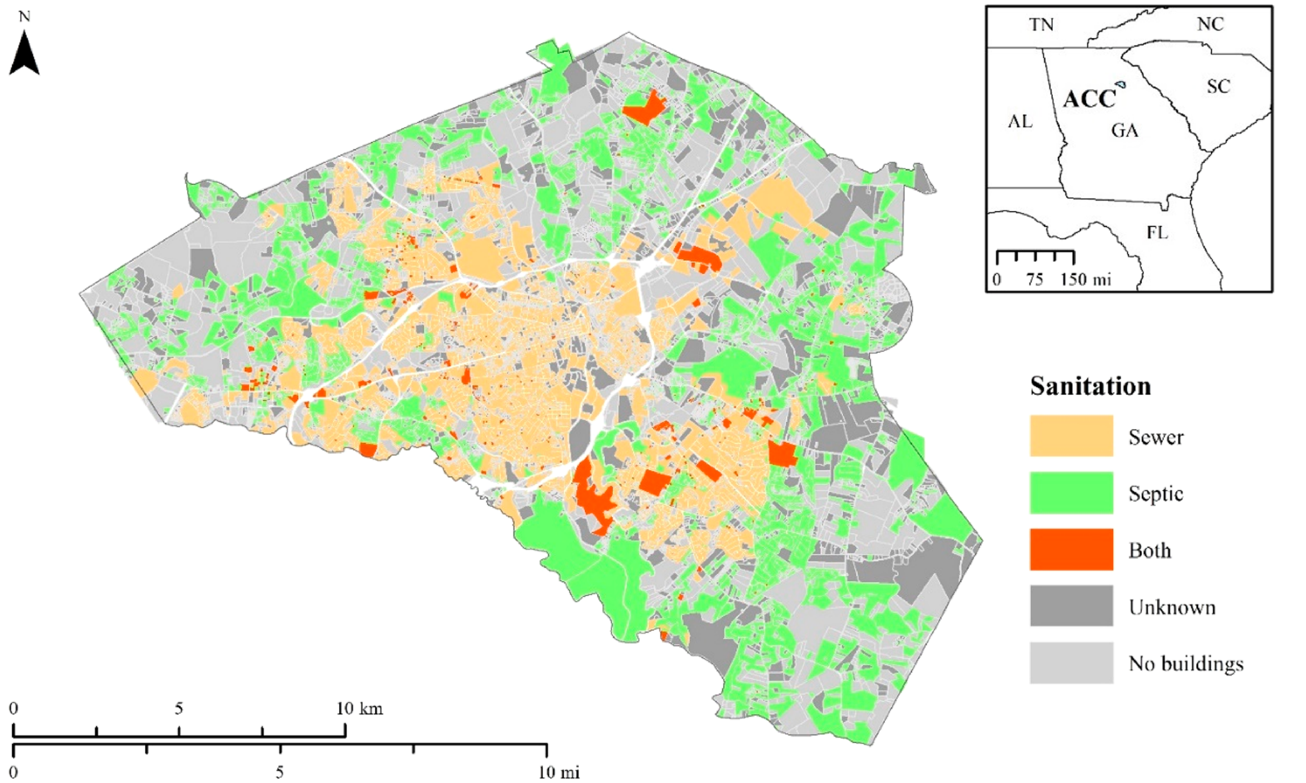

Figure 2. Distribution of the parcels in Athens-Clarke County that have sewerage and septage registered with the county. Parcels were designated with or without buildings (No buildings), known sewer connections (Sewer), known septic tanks (Septic), both types of wastewater infrastructure (Both), or unknown wastewater infrastructure (Unknown). A conceptual design of how the analysis was conducted is in Figure 1b and the number of parcels is detailed in Table 1.

quantity of wastewater infrastructure and demographic characteristics of their residents.[31,32]

The purpose of this study was to develop a framework to support local governments in assessing the condition of their septic infrastructure (Figure 1). We integrated a data set created by a municipal government with freely available environmental data to characterize septic infrastructure at the county level and develop an approach to assess the potential risk posed by septic systems. Subsequently, we used county-level data to evaluate methods local governments could employ to locate and enumerate septic systems when septic information was limited. We conducted our work in Athens Clarke County (ACC), Georgia in the southeastern United States (Figure 2). The wastewater infrastructure of ACC is representative of many local jurisdictions, as it is a heterogeneous mixture of septic systems and sewer lines. However, ACC is unlike many local governments, as the county has invested a large amount of resources and initiated new community−university partnerships to generate detailed information about septic infrastructure.

■ DATA AND METHODS

Data Sources. This work was conducted using data that were originally collected and organized by employees of ACC, a 314 km^2 county in northeast Georgia. The county has a population of approximately 124 000 people, of whom approximately 44% are nonwhite and approximately 36% live in poverty.[33] Geospatial layers of known septic locations, tax parcels, buildings, and sewer line locations were generated by multiple offices within the Department of Public Works in ACC using information from the state and local government. The county also provided the addresses of sewer connections in the county. We incorporated soil data derived from the US Department of Agriculture Soil Survey Geographic Database[34] and slope data derived from a 30 m resolution US Geological Survey National Elevation Data Set[35] into our analyses. Additionally, we calculated the distance to the nearest stream using the high-resolution US National Hydrography Data Set.[36] Socio-demographic data and the census block groups were downloaded from the US Bureau of the Census.[33]

We assessed the quality of the county septic data in two ways. First, we reviewed the known septic locations and associated data tables to make sure installation years were correct, duplicates were removed, and OWTS were accurately placed within their tax parcel (Figure 1a). Supplemental data, such as installation or repair forms, were associated with the majority of septic tank locations within the geodatabase. We used these documents to assign the installation year of systems with no assigned installation dates. We also used these documents to confirm the installation year of OWTS that were anomalously old (>60 years). Once the ages of the OWTS were verified and OWTS with no age data were purged from the data set, parcels with multiple OWTS were checked to determine if an OWTS was incorrectly duplicated on the parcel or if there was a multifamily home or parcel (e.g., mobile home park) that required multiple OWTS. Again, we used the supplemental forms that were associated within the county septic geodatabase to determine whether a parcel required multiple OWTS. During the duplicate check, we compared digitized OWTS locations to the information in the supplemental forms. We noted a high degree of accuracy and we used a small, randomly selected sample (∼100 additional OWTS) of parcels without multiple OWTS to confirm the locational accuracy across the data set. To

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assess whether the registered septic systems were likely to represent the majority of the septic systems in the county, we integrated geocoded sewer connection addresses with county-level parcel and building layers to estimate the number of parcels with permanent buildings or mobile homes that were not assigned wastewater treatment infrastructure (Figure 1b).

The septic data layer's year of installation and the location of a septic tank within a parcel were used to estimate the potential risk of environmental failure posed by aging and/or poorly placed septic tanks in ACC. Environmental failure is defined by the US EPA as adverse impacts at a distance with travel of contaminants through the subsurface.[10] The risk associated with OWTS placement was assessed by using policies set by the state of Georgia about the installation of septic systems.[37] These guidelines were informed by federal recommendations.[10] Briefly, we classified the OWTS using three characteristics: distance to nearest stream, soil type, and slope. OWTS that were placed within 25 ft (7.62 m) of a stream were considered at risk for distance to stream. OWTS that were placed in soils classified as unsuitable for septic were considered at risk for soil type, and OWTS placed in areas with greater than 25% slope were considered at risk for slope. Because the location of the OWTS within each parcel was not known, we assumed OWTS were located in the center of the parcel. Though this may not be an appropriate assumption in all jurisdictions, according to the soil data[34] we employed in the analysis, the soils in ACC are relatively homogeneous in the way they are classified for the placement of septic systems. Thus, we feel this was an appropriate assumption for our analysis. However, this assumption may not be valid if jurisdictions employ finer resolution soil data to support the placement of OWTS. It is important to note that ACC most likely uses higher resolution soil data to support OWTS placement decisions.

We evaluated potential environmental justice concerns by identifying septic systems in census blocks within the county where more than 30% of the population lives below the poverty line and/or more than half of the population is nonwhite. In addition to the descriptive statistics presented in this manuscript, we developed a logistic regression model to relate the census block group data to the parcel level occurrence of "at-risk" OWTS due to their age. The logistic regression models found a potential relationship between poverty and old OWTS (p-values <0.001), but the pseudo-r^2 values were less than 0.05, so we did not include these models in our results. This may have been due to mismatches in the spatial resolution of the census data (block) and OWTS data (parcel).

Using the detailed septic geodatabase curated by ACC, we assessed the efficacy of methods to support local jurisdictions to generate potential parcel-level septic locations without geocoded sewer information (Figure 1c). The county is constantly updating and adding information to this geodatabase and our analysis is only representative of the data set that we were given (data provided on November 2, 2018).

We combined county-derived tax parcel, building, and sewer line layers to identify the potential parcels that were serviced by sewers or are on septic and compared these results to the known septic systems and sewer connections in the county. We did this by completing a three step-process. The first step assumed that sewer line and parcel layer information is available, the second step assumed that an additional building layer information is available, and the third step assumed that the "building type" information is available as well. We initially developed a logistic regression model to estimate the parcels that could be on sewer. Property owners in the county are legally required to connect to the public sanitary sewer if the public sewer line is within 60.96 m (200 ft) of the property line.[38] Our estimate includes a factor of safety of 200 ft, as we did find some parcels on sewer in our study area that were placed further than 400 ft from a sewer line. Researchers in other jurisdictions may want to review and confirm these assumptions with relevant local water officials. The dependent variable was coded as 0 = no sewerage connection and 1 = sewerage connection present. The independent variables incorporated were "distance to sewer line" and "parcel size". The model was built using 75% of the available data and tested for accuracy on the remaining data set. Based on the results, we selected 0.7 as the threshold above which all parcels were predicted to be on sewer. This threshold may vary based on the quality and number of predictor variables used for building the logistic regression model. For instance, if fewer variables are available and the confidence on predictions was low, a higher threshold could be used in the analysis.

To ensure that the model was not data specific, but was statistically robust, we completed 1000 iterations on the model by independently sampling from the data set and then selected the model with the largest r^2 value (0.25). Subsequently, we excluded all parcels that were more than 600 ft away from a sewer line. We believe this distance is conservative in estimating the number of parcels because personal communication with regional water officials revealed that the typical industry standard is 121.92 m (400 ft). We subsequently removed parcels that had no buildings on them, and then we refined this step by removing parcels that did not include permanent buildings or mobile homes. After each step of the analysis, we compared the number of parcels we identified as either sewer or septic with the known locations of septic systems and geocoded sewer data in the county and calculated the number of parcels that were identified correctly. Because the county has extended sewerage through time, we assumed parcels that contained a septic tank but were also geocoded with sewer connections were on sewer.

Notably, a logistic regression model integrating census-block-level demographic data could effectively be developed for other jurisdictions (e.g. ref 39). However, our analyses revealed that they were not predictors of risk in our system. We want to be clear that the methods we used to generate possible parcel-level septic locations may not function for every site. Researchers could also evaluate the use of different or additional predictor variables, such as tax value of the property or age of any structures on the property, in their analyses.

■ RESULTS

Data Quality Analyses. The county maintains high-quality data pertaining to the known location of 9,776 septic tanks (Table 1). Of the data we were provided, only 693 OWTS, or 0.93% of the total were removed from the analysis because they lacked information about their installation year or were duplicates. Furthermore, by integrating parcel, building, and sewerage layers to identify permanent buildings on parcels without sewer connections, we were able to identify 87% of the OWTS in the county septic layer. Our analyses also suggest that the county may not have identified all of the OWTS that lie within its jurisdiction (Table 1; Figure 2). We identified 36 098 parcels with permanent buildings. More than 60%, or 23 139 of those parcels were associated with sewer connections, and 7911 of the parcels contained one of the septic systems in our septic layer, leaving 5048 parcels with permanent buildings with

Table 1. Evaluating Data for Efficacy in Identifying the Parcels with Septic Systems[a]

description of layers	estimate	county reported	unknown
total parcels in ACC		42 089	
total parcels with sewer		24 216	
parcels that could be on septic	17 873	8115	9758
parcels with buildings		36 837	
parcels with buildings on sewer		23 274	
parcels that could be on septic	13 563	8008	5555
parcels with permanent buildings or mobile homes		36 098	
parcels with subset buildings on sewer		23 139	
parcels that could be on septic	12 959	7911	5048

[a]Using county-generated layers of parcels, buildings, and sewer connections to compare known septic tank locations with parcels that may have septic tanks. The designation of "unknown" was assigned when there was no infrastructure assigned to specific parcels. These "unknowns" were determined through our analysis and do not signify that wastewater infrastructure within a given parcel is not registered with the county. A conceptual design of how the analysis was conducted is in Figure 1b and a map of the results is depicted in Figure 2.

unknown wastewater infrastructure (Table 1; Figure 2). Our classification of "unknown" relies on the data layers we used and the assumptions we made; it does not indicate the wastewater infrastructure within a given parcel is not documented within any county data resources. Rather, our "unknowns" may have been the products of integrating data sets from multiple county offices that were originally generated for different purposes.

OWTS-Specific Characteristics. Only 8% of the OWTS registered with the county were classified as a potential environmental risk due to their placement (Table 2; Figure 3). The majority of these OWTS were only classified with one of the three risk factors. A total of 688 OWTS were placed in poor soils. Thirty-six OWTS were at risk because of their distance to streams, and only two OWTS were classified as risky due to slope. Only 23 OWTS were characterized as risky for two of the three factors, and none of the OWTS fell into all three environmental risk categories (Table 2). To assess the potential impact of unregistered septic systems on the environment, we also analyzed the parcels with unknown wastewater infrastructure (n = 5048). Assuming the OWTS was placed in the center of the parcel, 336 or 7% of the unknown OWTS could be a potential environmental risk (Soil: 290 OWTS; Stream: 33 OWTS; Slope: 6 OWTS; Soil/Stream: 29 OWTS; Soil/Slope: 5 OWTS). In contrast, 6259 OWTS, or 69% of all OWTS in the ACC database present a potential risk because of their age. Of these OWTS, 1668 OWTS were between 26 and 35 years of age, 2049 of the OWTS were between 36 and 45 years of age, and approximately 28% of the OWTS, or 2524 OWTS, were more than 45 years old. Approximately 5% of all the OWTS registered with the county were classified with potential age and environmental risk factors (Table 2), and many of the OWTS classified with environmental risks were old. For example, of the 48 OWTS that were at risk due to their proximity to the nearest stream, 71% of them were also more than 25 years of age.

Approximately 64% of the area in the county (~201 km^2) is home to communities that are nonwhite and/or are living in poverty. These census block groups contain 5312 OWTS, or 58% of all of the OWTS registered in the county. Approximately 59% of the OWTS presenting potential age and/or environmental risk were located in these communities (Table 2; Figure 4). Of these OWTS, 439 present potential environmental risks, 3700 present potential risks due to age, and 284 present risks due to environmental factors and age. Additionally, 63% percent (n = 230 OWTS) of the parcels with unknown wastewater infrastructure that presented a potential environmental risk were located in areas populated by impoverished and/or nonwhite communities.

Table 2. Summary Table of the Characteristics of Known OWTS[b]

	totals		poverty only		race only		poverty and race	
summary (total #, % of total)								
OWTS registered by county	9083	100%	535	6%	3105	34%	1672	18%
OWTS with environmental risk	749	8%	56	7%	277	37%	106	14%
OWTS with risk from age	6259	69%	466	7%	1947	31%	1287	21%
OWTS with age and environmental risk	488	5%	50	10%	185	38%	49	10%
OWTS at risk from environmental conditions (total #, % of total)								
soil type	688	8%	48	7%	250	36%	102	15%
distance to stream	36	0%	3	8%	23	64%	2	6%
slope	2	0%	0	0%	0	0%	1	50%
soil and distance	12	0%	3	25%	4	33%	0	
soil and slope	11	0%	2	18%	0		1	9%
distance and slope	0		0		0		0	
soil, distance, and slope	0		0		0		0	
OWTS at risk from OWTS age (total #, % of total)								
26−35 years	1686	19%	69	4%	635	38%	292	17%
36−45 years	2049	23%	221	11%	700	34%	455	22%
>45 years	2524	28%	176	7%	612	24%	540	21%

[b]OWTS were evaluated for risk associated with their placement in the environment (i.e., soil type, slope, and distance to stream), with OWTS age (i.e, OWTS > 25 years of age), and for potential environmental justice concerns. Values in the "Totals" column include the total numbers of OWTS in each category, and the percentage of the total numbers of OWTS in each category. The number of OWTS in impoverished areas ("poverty": >30% of people living below the poverty line), in predominantly nonwhite neighborhoods ("race": >50% nonwhite population), and in predominantly nonwhite, impoverished areas ("poverty only and race only") are in the remaining columns. Percentage values in these three categories ("poverty only", "race only", and "poverty and race") are the percentages of the total number of OWTS in the corresponding row.

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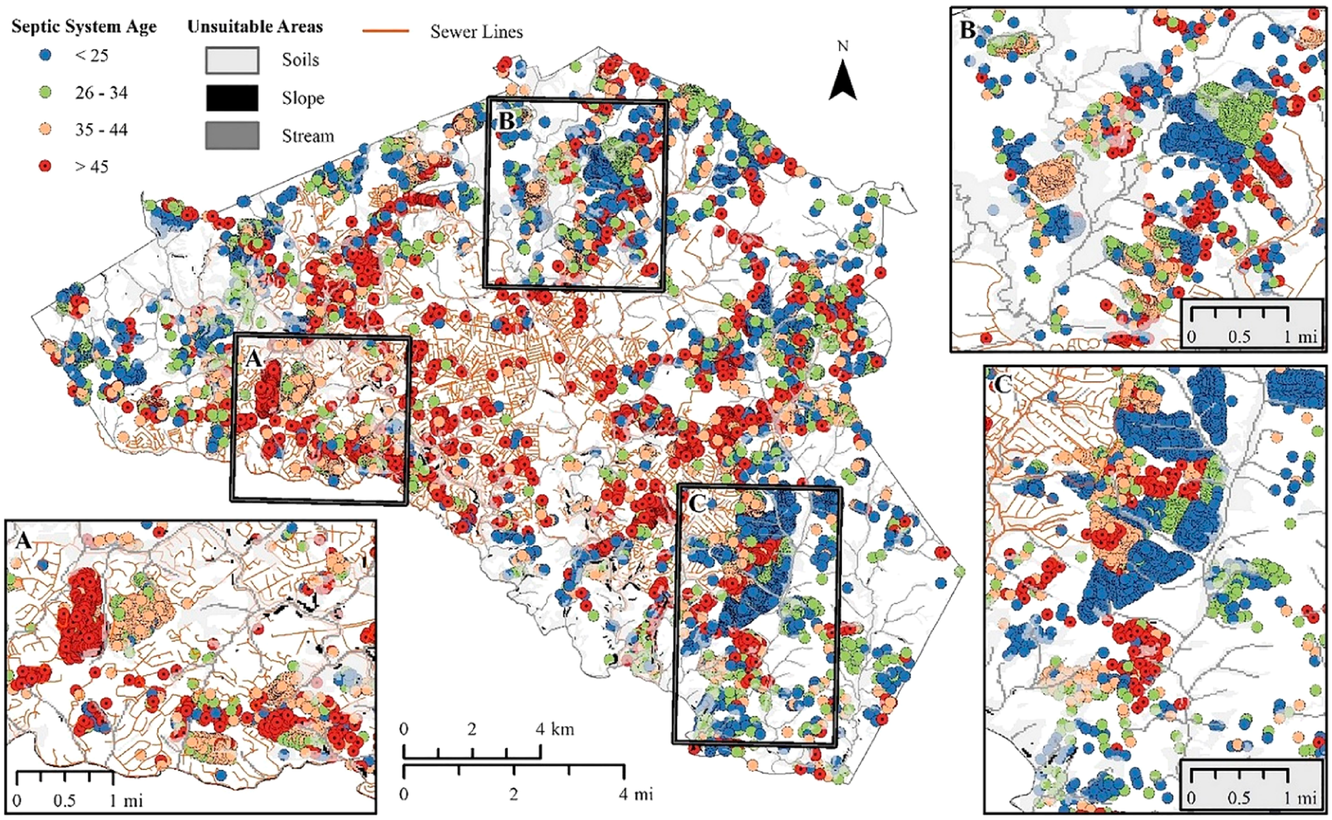

Figure 3. Distribution and classification of septic systems (n = 9083) in Athens-Clarke County, GA. Initial data were provided by the Athens-Clarke County. The OWTS numbers are detailed in Table 2. To emphasize the heterogeneity in factors including OWTS density and variability, environmental conditions, and the location of OWTS relative to stream networks within county lines, we highlight a few focal areas in the county that vary in all of these characteristics (A, B, C).

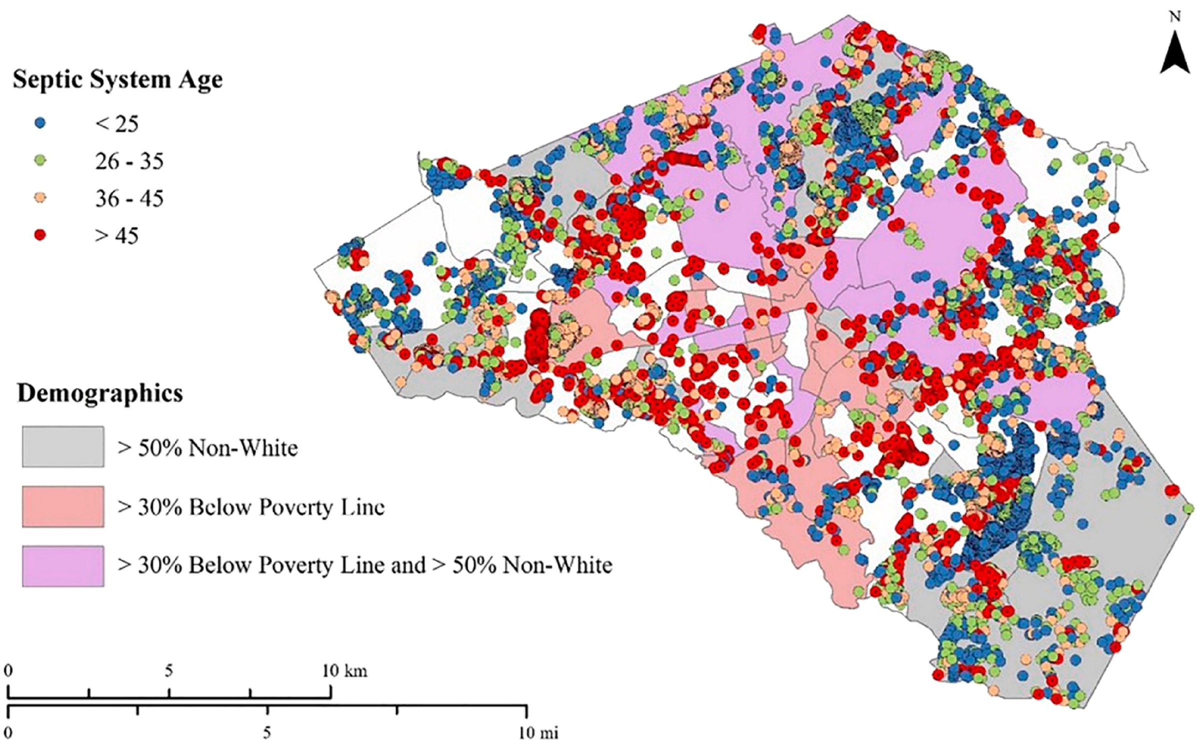

Figure 4. Septic tank age and distribution as related to income and communities of color. The OWTS numbers are detailed in Table 2.

Efficacy in Using Commonly-Available Data Sets to Locate Septic Systems. We joined the parcel and non-geocoded sewer layers, and we estimated that 30 230 of the 42 089 parcels could be on sewer and 11 859 parcels could be on

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Table 3. Identifying Parcels Using Septic Systems with Limited Data Resources[d]

description	estimate	county reported	correctly identified	incorrectly identified	unknown
total parcels in ACC		42 089			
parcels that could be on sewer	30 230	24 216	23 652	911	5667
parcels that could be on septic	11 859	8115	7204	564	4091
parcels with buildings		36 837			
parcels that could be on sewer	26 691	23 274	22 739	872	3080
parcels that could be on septic	10 146	8008	7136	535	2475
parcels with permanent buildings or mobile homes		36 098			
parcels with buildings that could be on sewer	26 354	23 139	22 610	856	2888
parcels with buildings that could be on septic	9744	7911	7055	529	2160

[d]County reported data are the numbers of parcels in the county with septic systems (parcels can have >1 system) and registered sewer connections. The "unknown" WWTI parcels were determined through our analysis and do not signify that wastewater infrastructure within a given parcel is not registered with the county. A conceptual design of how the analysis was conducted is in Figure 1c and a map of the results is depicted in Figure 5.

septic (Table 3; Figure 5). By comparing these estimates to the actual numbers maintained by the county, we were able to correctly identify 98% of the known parcels with sewer connections and 89% of the parcels with septic systems. Approximately 911 parcels with sewer connections (4% of the total number of registered connections) and 564 (7% of the total registered septic tanks) were identified incorrectly. A total of 5667 parcels that could have been on sewer and 4091 parcels that could have been on septic were not accounted for in the county data we were provided. County data indicated there were 409 parcels that had both septic systems and sewer connections. We assumed the overlap occurred as sewer lines were extended and parcels formerly on septic moved to sewer, as septic systems do not legally need to be removed after this process. Therefore, we classified the parcels that had both types of waste treatment as parcels with "actual" sewer connections, and we subtracted the 409 parcels from the "actual" septic systems. As we integrated parcels with buildings and parcels with permanent buildings, the number of parcels potentially on sewerage or septic that were classified with unknown wastewater treatment declined to 2888 parcels and 2160 parcels, respectively (Table 3). Following this step, we were able to identify 98% of the known sewer connections and 89% of the known septic systems with this effort. The results indicate the methods outlined in this study could be employed by local jurisdictions to develop spatially explicit, onsite WWTI data to support wastewater policy development and identify areas where WWTI may be lacking (Figure 6).

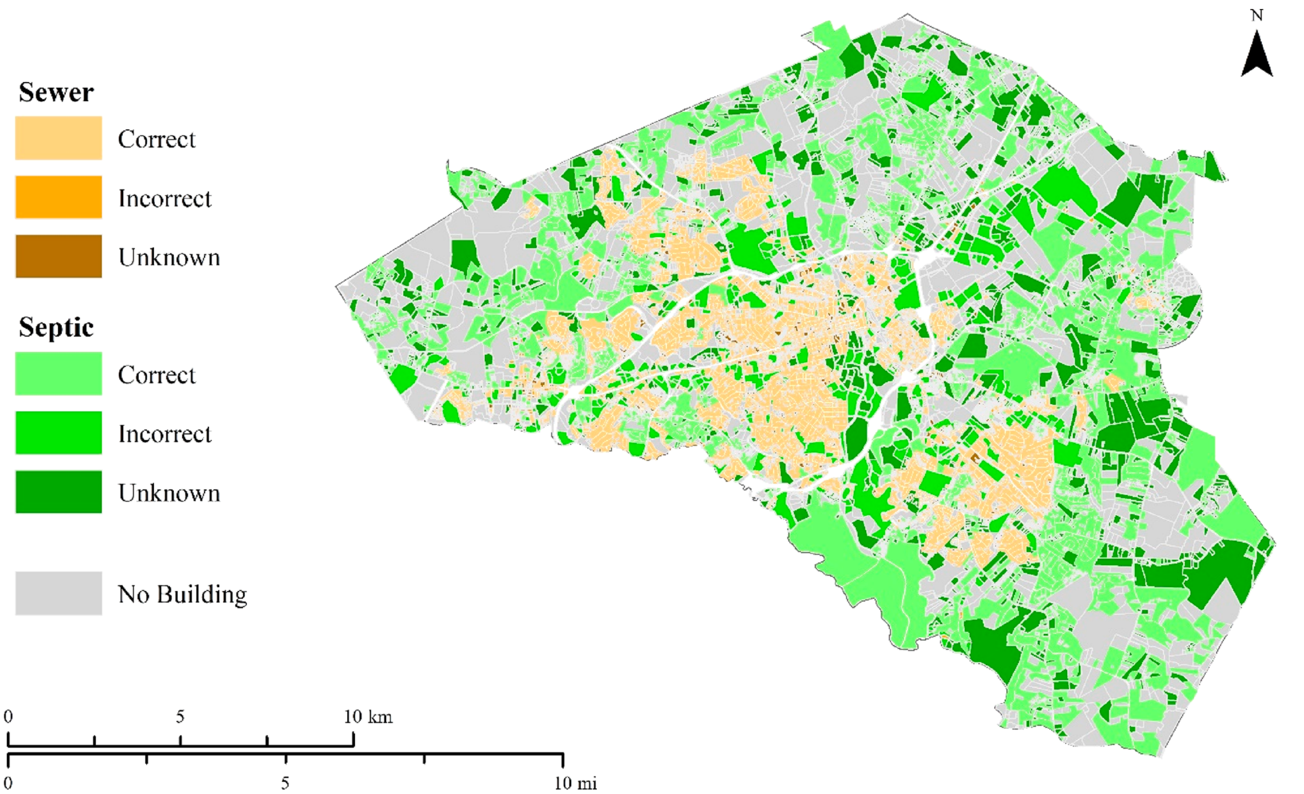

Figure 5. Predicting OWTS locations using parcel, building, and nongeocoded sewer data. Predictions were categorized as correct or incorrect using the locations of known septic systems (parcels can have >1 system) and geocoded sewer connections on parcels with permanent buildings or mobile homes.

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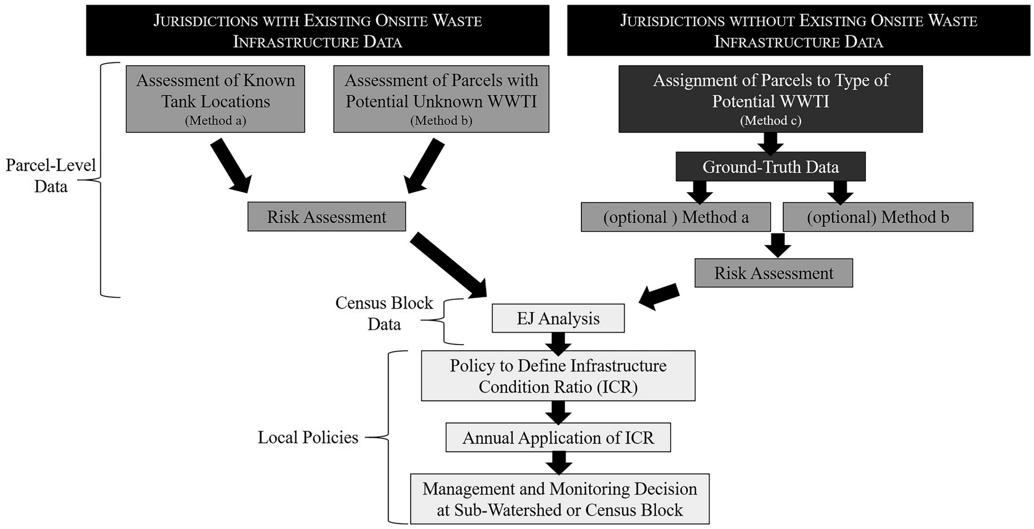

Figure 6. Potential decision-making strategy to enhance information about septic infrastructure and support policy development. Local jurisdictions can generate and integrate parcel-level data using census-level data to assess potential environmental justice concerns associated with aging and/or obsolete septic systems. Natural resource managers can use these data to calculate an infrastructure condition ratio, comparing the number of OWTS that are aging or otherwise potentially risky to the total number of OWTS within a given area in the county, to prioritize infrastructure development activities. If subsets of the data required support methods a or b are available, they can be used to ground-truth the information generated in method c.

■ DISCUSSION

One of the great challenges in addressing surface water pollution is to identify spatial and temporal variability of the contribution of septic systems to the pollution load.[2] The results from this study indicate that the primary threat posed by systems in ACC is not due to their placement within the landscape, but by the risk posed by exceptionally old systems. By integrating data sets generated by local and federal governments, we were able to identify OWTS at risk for failure in impoverished and/or nonwhite communities. This approach could support local governments in wastewater infrastructure planning and policy development, and potentially support local officials in proactively addressing environmental justice concerns. Our work also suggests that state and local governments with limited information about septic infrastructure may be able to effectively use readily available geospatial data sets to predict the parcel-level locations of septic systems within their jurisdictions to inform policy development and to establish environmental monitoring programs.

In the US, the placement of septic tanks is regulated at the state or local level and based on voluntary federal guidelines.[10,14,16] Therefore, the situation we documented in ACC has probably not happened by chance and may represent conditions in other US jurisdictions, as installation permits may being given out through relatively robust systems. This is especially true in regions with OWTS constructed after the 1970s, when more stringent regulations about septic installation became commonplace in the US.[14] Even with the county's concerted effort to develop septic data resources, we documented a large number of parcels (>5000 parcels) that contained permanent buildings that did not have wastewater treatment infrastructure registered within any of the county's geodatabases. Because sewer is a paid utility that is actively managed by the county, we suspect a great number of the parcels with unknown infrastructure may contain septic systems or other infrastructure that are not georegistered. Notably, our data do indicate that if all of the parcels that were categorized as "unknown" in this analysis did contain septic tanks, the majority of the OWTS would be legally acceptable if they were placed in the center of the parcels, so OWTS placement may still not be a problem.

Legal placement of OWTS within a parcel does not ensure that septic systems will not present risks to the environment or human health, and this is especially true in regions characterized by high septic densities. Human fecal contamination has been associated with the density of septic tanks in a watershed,[40] and septic systems have been linked to gastrointestinal illness in children[41] and chronic exposure to *Cryptosporidium*[42] in regions where well water is a primary source of drinking water. Climate change may also alter the contribution of septic systems to pollution, irrespective of system age, especially in coastal communities where sea-level rise may increase the frequency and intensity of wave inundation and storm surges that flood OWTS.[43,44] Research has also demonstrated that storm events can influence septic function and the flow of septic-derived pollutants into surface water.[45,46] Septic density may also be a factor defining the contribution of septic systems to pollution loads;[47] yet, our ability to predict how environmental conditions (e.g., soil type, weather conditions, climate) interact with septic density to influence the pollution load from onsite systems is still limited.[48]

Aging septic systems are commonly found in the US and around the globe; ACC is not the exception. Approximately 51% of all of the registered OWTS in the county were built prior to 1985, and approximately 28% of the registered OWTS were constructed before 1975. OWTS age has been repeatedly linked to declining quality of surface waters.[2] As many of the OWTS in the county and homes on parcels without any registered treatment systems may have been built before the Clean Water Act, residents may not have been required to retrofit older or nonexisting systems to newer environmental standards.[29,49]

Younger OWTS may also fail if they are not constructed or maintained appropriately. The capacity, construction, and technology of onsite waste systems is highly variable,[16] and this influences the ability of a OWTS to process waste.[50−52] Surveys frequently demonstrate that a large proportion of systems are subject to failure due to poor construction, the undersizing of systems relative to their hydraulic loads, or improperly assessed soil capacity in drain fields (e.g. ref 48) Septic systems are sized based on the original size and characteristics of the home. Additional bathrooms, higher densities of inhabitants, and the addition of garbage disposals to a home may not legally require the resizing of a septic system, but may substantially increase the volume of the waste flowing into the system, compromising system function.[18] Relatively recent work suggests that septic systems that appear to be functioning may contribute to the contamination of surface water.[53] It is also important to note that it is exceptionally difficult to ensure that mobile homes are using permitted systems, as they can move to new properties and connect to existing water lines without permission from the local or state government. Therefore, when possible, local jurisdictions may also want to incorporate information about mobile home permitting, inhabitant density, and home renovations (e.g., resizing or the addition of garbage disposals) into their OWTS layers to assess potential risk.

Notably, our analysis produced thousands of parcels that had "unknown" wastewater infrastructure associated with them (11% of the parcels that could be on sewer systems and 22% of the parcels that could be on septic; Table 3). Again, our designation of either "unknown" or "incorrectly identified" WWTI for a given parcel was the result from this analysis that was conducted using the specific data layers we were provided. We emphasize that these classifications do not signify that wastewater infrastructure within a given parcel is not registered in some way with the county. However, they do highlight the challenge many jurisdictions will most likely face as they attempt to integrate information from diverse entities within the local government. For instance, the act of combining the parcels, buildings, and geocoded sewer connection layers to assess the WWTI of the county (Table 1; Figures 1b and 2) generated error in our parcel assignments that was evidenced by a decline in the number of county-reported parcels on septic or sewer with each step of our process. Some of the parcels without registered wastewater treatment infrastructure may also be using "straight piping" or direct surface water discharge. Especially in rural areas of the southeastern US and Appalachia, there is widespread documentation of straight piping,[28,29,32,49,54] as people who do not have the financial means to install on-site systems will often resort to constructing their own wastewater piping.[27] Coupled with these data, our work suggests that natural resource managers may want to invest in programming to identify and address issues associated with direct surface water discharge, especially in jurisdictions with older buildings with unknown wastewater treatment infrastructure.

In the US, data relating socio-demographic information with access to sanitation are relatively limited, as national census data on sanitation have not been collected since 1990.[28] Yet, research in both urban and rural regions has repeatedly demonstrated that access to effective wastewater treatment infrastructure can be related to income and race.[29,49,55,56] For example, approximately 90% of the residents in Wilcox County, a predominantly Black county in Alabama, have unpermitted sewage systems that are dominated by straight pipes. Estimates suggest that 550 000 gallons of raw sewage from Wilcox enters the Alabama River watershed every day, and decades of contamination from aging and obsolete wastewater infrastructure have supported the persistence of hookworm in the county.[28] Recent work documents that this is not just a problem relegated to southeastern and Appalachian states; rural communities from western and centrally located states, including Alaska, California, Michigan, and Ohio, face similar challenges from inadequate sanitation.[28] We were unable to run additional statistical analyses to relate socio-demographic data with OWTS-level data due to the difference in the spatial resolution of our data sets. Relative to many states within the US, Georgia has a large number of relatively small counties. Therefore, we could not effectively aggregate parcel-level data to the block-group level to conduct meaningful analyses. Additional data that are spatially comparable are needed at the local, state, national, and tribal level to document the condition of wastewater infrastructure in order to develop effective OWTS policies.

Maintenance may substantially increase the life of a septic system; however, estimates indicate only about half of OWTS owners in the US actively maintain their systems.[14] Appropriate maintenance (i.e., pumping and OWTS replacement) can cost several hundred to several thousand USD, costs that exceed the economic realities of many landowners. State and local laws and policies often criminalize people who fail to comply with environmental regulations associated with sanitation. Yet, it is often the lack of financial means, rather than a lack of will, that prevents residents from engaging in legal wastewater treatment.[55] Policies focused on addressing inadequate infrastructure and supporting OWTS maintenance (e.g., regular inspections and pumping) may have the greatest potential to address environmental and health issues associated with septic pollution, especially in ACC where a large proportion of the community lives in poverty. State and local governments may also want to develop programs that decriminalize inadequate sanitation and encourage residents to seek support to address issues with unpermitted systems, in addition to providing financial support for the installation and maintenance of permitted OWTS and sewer connections.[23,49,54,55]

By employing some of the methods outlined in this study, natural resource managers can generate geospatial data layers to assess their onsite WWTI and target specific areas within their jurisdiction for intensive monitoring of potentially problematic septic systems. For example, natural resource managers could use newly developed layers to annually calculate an infrastructure condition ratio of OWTS that are aging or otherwise potentially "at risk" to the total number of OWTS within a given area (e.g., subwatershed or census block). Our data highlight that both potential OWTS risk and socio-demographic characteristics can be heterogeneously distributed within a jurisdiction (see Figures 3 and 4). This type of analysis may support efforts to prioritize the distribution of public resources to support OWTS maintenance in areas within a county that present environmental or environmental justice concerns.

Onsite waste management systems are a fundamental part of global wastewater infrastructure. When they are placed appropriately, are subject to regular maintenance, and are effectively monitored, septic systems are often the most economically sound and ecologically sustainable options for wastewater treatment. Countries such as the US, where environmental regulations that were established in the mid- to late-1900s prompted the expansion of onsite waste systems, are now subject to environmental and public health related issues due to aging and obsolete septic systems. However, even in a county such as ACC, that is proactively attempting to characterize the septic infrastructure within their jurisdiction, assessing the location and condition of septic systems is a substantial challenge. In many jurisdictions, OWTS records may limited to paper records stored at the health department,

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rendering this type of analysis exceptionally difficult. More tools are needed to support effective natural resource management and forward-thinking urban planning, and empower local officials with the information needed to make informed decisions about wastewater treatment infrastructure. We have demonstrated that even when their data are very limited, jurisdictions can integrate widely available data sets to assess the condition of their septic networks and inform wastewater policy.

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Notes

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