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Assessing relationships between onsite wastewater treatment system maintenance patterns and system-level variables

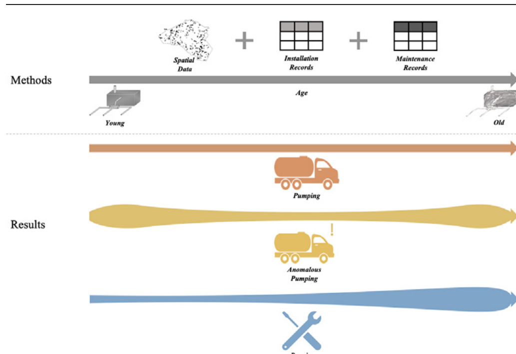
Kyle N. Connelly[a,b,*], Seth J. Wenger[a,b], Nandita Gaur[c], Jacob M. Bateman McDonald[d], Mike Occhipinti[e], Krista A. Capps[a,f]

[a] Odum School of Ecology, University of Georgia, Athens, GA 30602, USA
[b] The River Basin Center, University of Georgia, Athens, GA 30602, USA
[c] Department of Crop and Soil Sciences, University of Georgia, Athens, GA 30602, USA
[d] Lewis F. Rogers Institute for Environmental and Spatial Analysis, University of North Georgia, Oakwood, GA 30566, USA
[e] Athens-Clarke County Unified Government, Snipes Water Resources Building, Athens, GA 30601, USA
[f] Savannah River Ecology Laboratory, University of Georgia, Aiken, SC 29802, USA

HIGHLIGHTS

- Aging onsite wastewater treatment systems pose health and environmental risks.
- A novel approach is employed to assess septic system condition at broad scales.
- Older septic systems (>50 years) are more likely to be repaired.
- Newer septic systems (2–10 years) and older systems both show signs of failure.
- Leveraging existing infrastructure datasets can reduce site assessment costs.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally, millions of households rely on onsite wastewater treatment systems (OWTSs), such as septic systems, to safely treat and dispose of wastewater. Conventional subsurface OWTSs are a common and affordable option for many landowners, and effectively remove pathogenic and nutrient pollution from wastewater when properly sited and maintained. However, OWTSs can also be a source of nonpoint pollution in watersheds when they are not functioning properly. To better understand the drivers of OWTS maintenance and failure, we explored relationships between OWTS age, environmental characteristics (edaphic conditions, topographic wetness index, and distance to stream), and repair and pumping records for OWTSs in Athens-Clarke County, Georgia, USA. Repair records indicated that 7.8 % of the 8826 OWTSs in the study were repaired over a 78-year period and that the median age of a repaired OWTSs was 65 years old. Pumping records showed that 12.2 % of the OWTSs were pumped in a 38-month period (an annualized rate of 5.7 %). The suite of widely available environmental variables we used as predictors were likely not granular enough to detect patterns of individual system maintenance at this scale. However, we found that the oldest OWTSs (>50 years) had the highest probabilities of being repaired and exhibiting signs of hydraulic failure. Notably, new OWTSs (2–10 years) were nearly as likely as the oldest systems to exhibit signs of hydraulic failure. These findings suggest that repair and replacement efforts should target older systems that are at or near the end of their serviceable life, and, in addition to continually monitoring older systems, all OWTSs should be inspected one

* Corresponding author at: Southeastern States District Office, Bureau of Land Management, 273 Market St., Flowood, MS 39232, USA.
E-mail addresses: kyle.connelly@uga.edu (K.N. Connelly), swenger@uga.edu (S.J. Wenger), nandita.gaur@uga.edu (N. Gaur), jacob.mcdonald@ung.edu (J.M. Bateman McDonald), mike.occhipinti@accgov.com (M. Occhipinti), kcapps@uga.edu (K.A. Capps).

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year after installation. By leveraging data that may already exist, practitioners in other localities can use this reproducible approach to estimate the performance of OWTSs. Our data and methods will support efforts to prioritize wastewater infrastructure investments and policies.

1. Introduction

Approximately one-fifth of American homes rely on onsite wastewater treatment systems (OWTSs), such as septic systems, to dispose of their sewage (Eggers and Thackeray, 2007; US Census Bureau, 2008). In total, OWTSs process approximately 4 billion gallons of wastewater per day in the United States (US) (US Environmental Protection Agency, 2013). Subsurface OWTSs are the most common onsite wastewater treatment option, as they offer an affordable alternative to central sewer system expansion (US Environmental Protection Agency, 1997) and thus tend to serve rural and suburban residential areas beyond the extent of sewer networks. When properly designed, installed, and maintained, OWTSs can effectively remove pathogenic (Bouma et al., 1972; Van Cuyk et al., 2004) and nutrient (Stewart and Reneau, 1988; Walker et al., 1973) pollution from wastewater. However, they can also become sources of nonpoint pollution in watersheds where they are malfunctioning or improperly maintained (Arnscheidt et al., 2007; Katz et al., 2010; Macintosh et al., 2011).

Installation and site-specific factors can affect OWTS function and lead to increased risk of hydraulic failure, where untreated effluent ponds on the ground surface, emerges from slopes, and/or backs up into the OWTS tank or home (Carroll et al., 2006; Collick et al., 2006; Swann, 2001). Conventional OWTSs have three primary components that are integral to their performance: (i) the septic tank, which retains most of the influent biosolids and grease, (ii) the drainfield, which transmits wastewater effluent from the septic tank to local soils, and (iii) the receiving soils, which absorb water and process contaminants (Otis et al., 1980; US Environmental Protection Agency, 2002). Characteristics that influence OWTS function include edaphic and geologic conditions, water table dynamics, landscape position and slope, and tank and drainfield size (Dunne and Leopold, 1978; Otis et al., 1980). For instance, drainfields rely on spatially heterogeneous soil biogeochemical processes to treat OWTS effluent, but the US Environmental Protection Agency (US EPA) estimates that only one-third of the nation's land area has soils suitable for conventional OWTSs (US Environmental Protection Agency, 2002). Therefore, it is likely that a significant portion of OWTSs are not functioning effectively due to improper siting and subsequent performance issues (e.g., Goonetilleke and Dawes, 2001). Three well-recognized and potentially interrelated subsurface site characteristics that may impede drainfield effectiveness are the receiving soil's hydraulic conductivity, the presence of low-conductivity or impermeable restrictive layers, and depth to water table (Collick et al., 2006; Otis et al., 1980; Siegrist et al., 2000). Gunady et al. (2015) documented that ground and surface water intrusion, improper installation, unsuitable soils, and inadequate system size were leading causes of OWTS failure in a survey of local governments in Western Australia. Additionally, other topographic site characteristics that control drainage patterns such as slope, curvature (i.e., convexity versus concavity), and upslope contributing area may influence OWTS function at the site level (Collick et al., 2006; Dawes and Goonetilleke, 2003; Hassett et al., 2007; US Environmental Protection Agency, 2002). Because of the potential for partially treated wastewater to leach into ground or surface waters, the siting and design of OWTSs has significant implications for community health and drinking water supplies (Gold and Sims, 2000; Siegrist et al., 2000; Van Cuyk and Siegrist, 2001).

Regular maintenance, including desludging in which biosolids are pumped from the OWTS tank, is critical to ensure OWTSs function properly. The US EPA recommends OWTS owners get their systems inspected every three years and pumped either every three to five years or when biosolids in the OWTS tank exceed 30 % of its volume (US Environmental Protection Agency, 2005a, 2002). However, these guidelines are not often followed because the cost of maintenance can be substantial (Kohler et al., 2016a; Williams et al., 2004). Homeowners may also choose not to adhere to these guidelines unless signs of hydraulic OWTS failure, such as sewage backflow into the house or ponding within the drainfield, are apparent. The diffuse nature of pollution from failing OWTSs and a general lack of understanding about subsurface flow within drainfields (Beal et al., 2005; Cardona, 1998) make it difficult to attribute downstream water degradation to any single OWTS; therefore, the environmental costs of these malfunctioning systems are borne by society, rather than individual owners (Mohamed, 2009; Pugel, 2019). Programs that replace failing systems (e.g., Hughes and Simonson, 2005; US Environmental Protection Agency, 2020) subsidize the costs of OWTS repairs or replacement. However, jurisdictions can face resistance from homeowners when administering monitoring programs (Corry, 2003). For instance, residents in Ozaukee County, Wisconsin were reported to have an initial adherence rate of only 51 % to a local ordinance which mandated annual OWTS tank inspections and full system assessments every three years (Benson, 2003). Because they often rely on complaints from neighbors or downstream landowners, programs that incentivize OWTS repair and replacement tend to retroactively address OWTS failures rather than supporting proactive planning to prevent future environmental contamination. Finally, and remarkably, some homeowners may not even be aware that they have an OWTS (Goonetilleke and Dawes, 2001), and thus homeowner maintenance or inspection would not occur unless obvious hydraulic failure ensues.

In general, OWTS infrastructure in the US is aging (American Society of Civil Engineers, 2021) and failures may be increasingly common as systems deteriorate. Studies of drainfield effluent acceptance rates suggest that OWTSs can remain hydraulically operational for 11 to >30 years (Siegrist et al., 2000), but approximately half of OWTSs 19 to 27 years old can be expected to show evidence of failure (Clayton, 1974; Winneberger, 1975). Though environmental site characteristics have been shown to affect the performance of OWTSs, system age may be a more ubiquitous predictor of OWTS condition and risk. A recent study by Capps et al. (2020) found that 8 % of the analyzed OWTSs posed a potential environmental risk due to the topographic, hydrologic, or edaphic characteristics of the system's placement. However, 69 % of the OWTSs in the study presented potential environmental risks due to their age (> 25 years). Because OWTSs are typically installed in clusters during housing development, failures also may be clustered in space and time. Yet, it is unclear how OWTS siting characteristics and age relate to maintenance patterns over the life of these systems.

Due to their decentralized nature and the general lack of available data for privately-owned OWTSs (Withers et al., 2014), research has generally focused on the environmental effects of OWTSs above density thresholds at the watershed scale (e.g., Borchardt et al., 2003; Oliver et al., 2014; Yates, 1985). There are far fewer studies on the impacts of individual faulty or ill-maintained OWTSs on water quality; yet, many state (Georgia Department of Public Health, 2019a, 2019b) and federal (US Environmental Protection Agency, 2003, 2002) guidelines highlight the potential effect poorly maintained systems may have on surface and groundwater resources. Work by Macintosh et al. (2011) in three rural catchments in north Ireland found that replacing malfunctioning OWTSs could result in reduced phosphorus concentrations downstream. Identifying the site-level characteristics of OWTSs that are at higher risk of failure is especially valuable to resource managers who are tasked with ensuring environmental and community health.

To study the drivers of OWTS maintenance and failure, we explored relationships between OWTS age, environmental characteristics, and repair and pumping records for OWTSs in Athens-Clarke County, Georgia, USA.

We collaborated with the local government to leverage a 46-year OWTS repair dataset (May 1972 – March 2018) and an approximately three-year (January 2017 – February 2020) dataset of OWTS tank pumping records. Our overarching goal was to use records to make inferences about OWTS condition over a broad spatial scale and to identify regions of concern within the county. Tools available for water management practitioners to assess their decentralized wastewater infrastructure typically focus on pollutant attenuation capability (e.g., Siegrist et al., 2000), whereas few studies have used actual OWTS maintenance or repair data to estimate patterns of system failure at scale and make actionable recommendations (e.g., Kohler et al., 2016a, 2016b). Therefore, we developed and tested a new approach that leverages existing maintenance data to support proactive OWTS assessment. Specifically, we identified OWTSs with pumping patterns that were indicative of failing systems (hereafter “anomalous pumping”) based on US EPA maintenance guidelines and/or the volume pumped from each system. First, we tested the ability of OWTS age and site characteristics to explain variability in repair, pumping, and anomalous pumping datasets. Best-fit regression models were used to develop probability curves to estimate the likelihood of OWTSs to be repaired or to exhibit anomalous pumping. Secondly, we assessed relationships between systems with repair records and those that exhibited anomalous pumping to test whether anomalous pumping may be a correlate of necessary repairs. Finally, we calculated the proportion of OWTSs that were pumped and then subsequently repaired within three years, which could indicate that the homeowner knew that their system needed additional maintenance.

2. Materials and methods

2.1. Study area

Athens-Clarke County (ACC) is located in northeast Georgia. With a land area of approximately 314 km^2, ACC is Georgia's smallest county by area and the state's sixth most populous metropolitan area, with an estimated 126,913 residents (US Census Bureau, 2019). Approximately 75 % of ACC residents are serviced by the central sewer system and nearly 32,000 residents depend on OWTSs (Athens-Clarke County Public Utilities Department, 2020). To guide infrastructure decisions, ACC has invested substantial resources into developing a county-wide geospatial dataset of all OWTSs, their ages, volumetric tank capacities, and repair and desludging histories (Capps et al., 2020).

2.2. Pumping and repair data

The county provided spatial and tabular data for all registered OWTSs in the study area (n = 9802), from which we filtered out occurrences of missing data, abandoned systems, those with accountable damage (e.g., house fires, windthrown trees), and records with uncertain geolocations (Fig. 1). We used methods modeled after Capps et al. (2020) to verify the locational accuracy of a subset of the remaining OWTSs. Installation dates of OWTSs in this dataset with high locational accuracy (n = 8826) ranged from January 1940 – March 2018. With these cleaned data, we filtered out points with missing predictor values, which were mostly OWTSs on the periphery of the study area (refined dataset n = 8786; Supplementary Materials 1). Subsequently, we calculated system age in years based on the number of years between system installation and October 28, 2020 (the date of data retrieval). Repair records for OWTSs (May 1972 – March 2018), which were submitted to ACC's Department of Public Health when repair work was conducted on any OWTS in the jurisdiction, were used to calculate a binary response of whether each OWTS was repaired (n = 690; Fig. 2).

To examine OWTS pumping patterns, the dataset was filtered to remove records without specified septic tank capacities and those with missing predictor values (refined dataset n = 7676). We combined this subset of OWTSs with information from >3000 OWTS tank pumping manifests (January 2017 – February 2020), which were recorded when septic

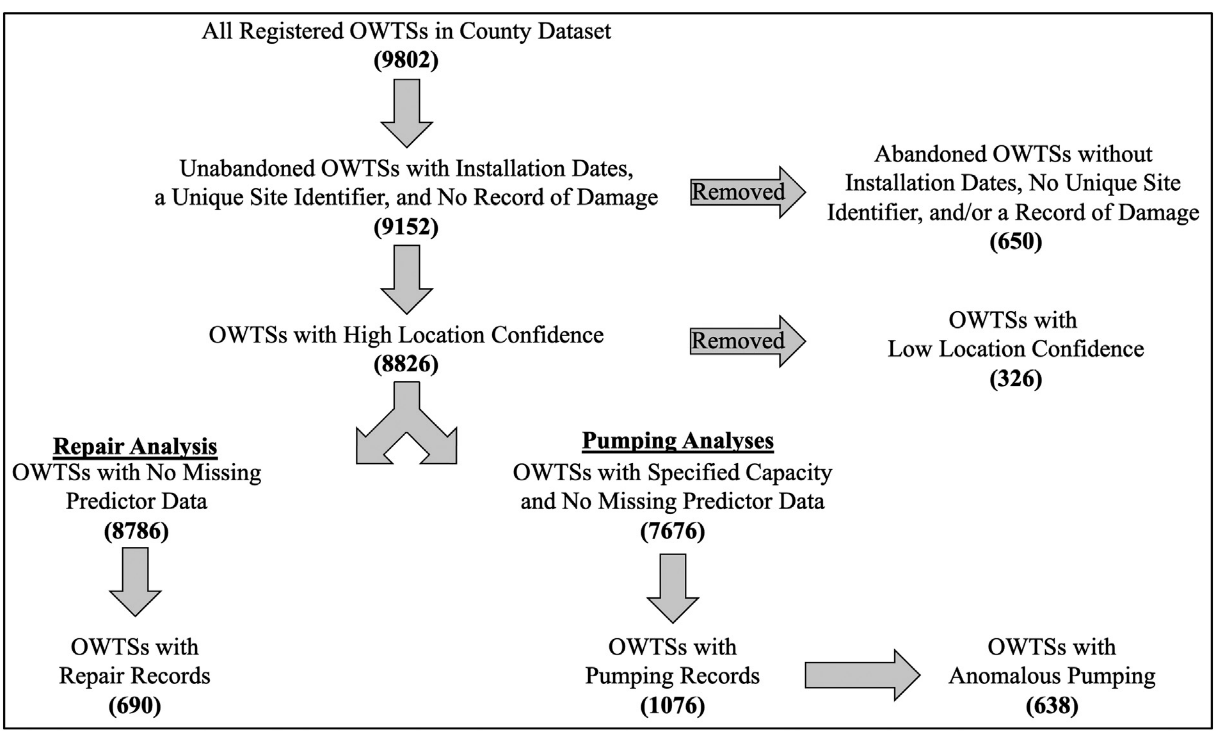

Fig. 1. Processes used to prepare the dataset for the repair and pumping analyses. Date of installations for the cleaned dataset with high location confidence ranged from January 1940 – March 2018. OWTS repair records (May 1972 – March 2018) were submitted to the Athens-Clarke County Department of Public Health when repair work was conducted at the location. Pumping records (January 2017 – February 2020) were collated from pumping manifests submitted to the Public Utilities Department when pumping companies disposed of septage at the Cedar Creek Water Reclamation Facility. Data included in the repair and pumping analyses are not exclusive, as all data points in the pumping analyses are a subset of data in the repair analysis, with the additional restriction of requiring a specified OWTS tank capacity. The corresponding number of records in each dataset or removal are indicated by the bold number in parentheses.

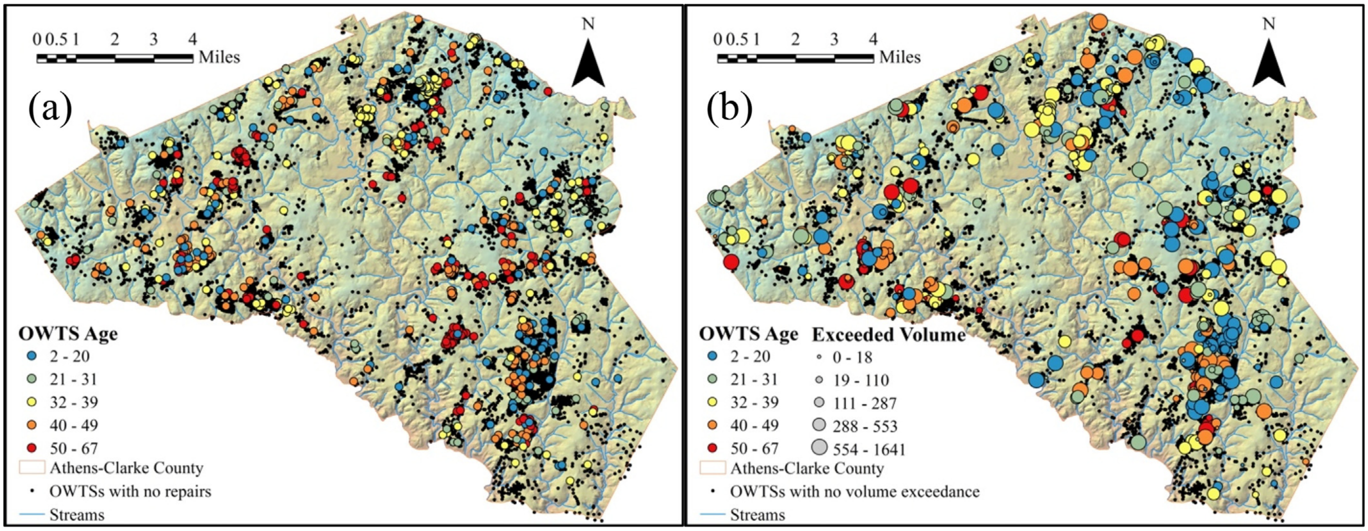

Fig. 2. (a) Age and spatial distribution of repaired OWTSs in Athens-Clarke County ($n = 690$). County installation records range from January 1940 – March 2018 and repair dates range from May 1972 – March 2018. The US EPA suggests a serviceable OWTS life of approximately 15–40 years depending on siting and maintenance conditions (US Environmental Protection Agency, 2017). (b) Age, spatial distribution, and maximum volume exceedance (gallons) of pumped OWTS tanks in a 38-month period of pumping records (January 2017 – February 2020; $n = 576$). Maximum volume exceedance was calculated as the difference between the recorded septage volume and the installed OWTS tank size. Data were retrieved in October 2020. The dataset of all registered OWTS locations provided by the county were filtered (see Fig. 1). Those OWTSs with no repair records ($n = 8096$) or that were either not pumped or did not have a volume exceedance pump ($n = 8210$) are displayed to provide context to those systems with repairs or anomalous pumping. A shaded relief layer and stream networks were included to emphasize the spatial heterogeneity of OWTS maintenance.

pumping trucks unloaded biosolids at ACC's Cedar Creek Water Reclamation Facility. The scale used to estimate septic truck load in gallons at this facility was intermittently out of service during the period of record. During these times, discharged volumes were estimated by the OWTS pumpers, though as the pumping companies are charged by gallon (Shaw-Burgess and Bloyer, 2020), these values may include underestimates, as it may have been beneficial for them to report lower, more conservative, volumes. There were also instances of pumping events at addresses that were not yet entered into the county's OWTS location dataset. Manifest records from addresses without registered OWTS point locations may be the result of illegally installed systems, exceptionally old units that predate record-keeping, missing county records, or incorrectly entered addresses. As registered locations could not be confirmed for these records, these manifests were eliminated from the pumping analysis of this study. A total of 1605 pumping events were associated with points in the refined dataset. Address, pumped volume, and date from each manifest were associated with the OWTS locations in the refined dataset and a binary response of pumping/no pumping was determined for each of the 7676 tanks in the refined dataset.

The Cedar Creek Water Reclamation Facility in ACC charges relatively low prices (Athens-Clarke County Public Utilities Department, 2021) for septage disposal and is one of the only treatment plants in a multicounty area that accepts septage (Georgia Environmental Protection Division, 2017). Hence, we assumed that if an OWTS tank in ACC was pumped in this 38-month period, there would be a record of the event in the county's manifests. We also assumed that all OWTSs were maintained legally. In other words, we have no records for homes that straight pipe raw sewage off their property or for pumpers who illegally dispose of their septage. To identify systems with anomalous pumping, we subset the total population of OWTSs with manifest records based upon binary arguments of whether (i) the OWTS had been pumped twice or more, thereby exceeding the US EPA's guideline of one pump per three to five years, and/or (ii) the pumped volume recorded on the manifest exceeded the tank capacity listed in county installation records. We assumed these instances of volume exceedance could be indicative of hydraulic failure and subsequent backup of effluent into the OWTS tank.

2.3. Spatial layers

To characterize site conditions, we used widely available elevation, soil, and river/stream (flowline) datasets. Local topographic characteristics such as slope, curvature, and upslope contributing area may contribute to drainfield saturation and system backups. To explore this phenomenon, we used a 30-m resolution digital elevation model from the US Geological Survey (2013) to calculate the topographic wetness index (TWI) in the study area. The TWI is a unitless approximation of soil moisture as a function of local topography and upslope contributing area (Beven and Kirby, 1979) and has been used to assess rain-derived flooding risk in land use planning (Pourali et al., 2016). The TWI was calculated using Eq. (1):

$$TWI = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (1)$$

where TWI is the wetness index, α is the upslope contributing area, and tanβ is the steepest local slope. We used the Terrain Analysis Using Digital Elevation Models (TauDEM) ArcGIS toolbox (Tarboton, 2016) in Esri's ArcMap v.10.7 (Esri, 2019) to calculate slope, flow direction, and contributing area using the D-infinity method (we added a value of 1.0e-6 to 0 slopes to prevent division by zero). A raster layer of Euclidean distance to stream was calculated using river and stream (flowline) data from the National Hydrography Dataset Plus High Resolution dataset (US Geological Survey, 2018) to estimate each OWTS's potential exposure to saturation due to overbank flooding or near-stream water table dynamics (i.e., variable source areas with saturation excess flow).

We did not have access to county soil assessments, which are used to determine OWTS drainfield installation suitability. Therefore, we analyzed Gridded Soil Survey Geographic Database (gSSURGO) data in ArcMap (Soil Survey Staff, 2020a, 2020b). The edaphic data used to permit OWTSs are based on high resolution soil maps or in-situ observations, while gSSURGO is an interpolated dataset that lacks onsite observations in many areas. Although soil values in this dataset are likely correlated with local conditions, gSSURGO data can differ slightly from the precise data that OWTS permitters often employ. Gridded soil values for saturated hydraulic conductivity were calculated using a weighted average of soil conditions between 30 and 183 cm below the surface, as Georgia Department of Public Health regulations necessitate drainfield pipe installations to occur 15-30 cm (6-12in) below the soil surface.[43] Gridded values for average depth to seasonal water table were calculated using the monthly (January–December) water table depth estimates available in gSSURGO. Values for depth to restrictive layer were calculated across the study area using the gSSURGO database.

2.4. Model selection and statistical analysis

To test whether site-level environmental conditions could predict OWTS maintenance, we developed and subsequently tested candidate and null models for each binary response variable (repaired/no repairs, pumping/no pumping, and anomalous pumping/no anomalous pumping) using logistic regression. As the focus of our analysis was the relationship between the environmental conditions of OWTSs and their maintenance histories, we did not include any socio-economic or demographic indicators in our candidate models. We defined models to test combinations of the following variables: OWTS age (years between installation and October 2020), TWI, distance to stream, and three soil variables: saturated hydraulic conductivity, depth to restrictive layer, and depth to seasonal water table (Table 1). We tested a quadratic term for age because we hypothesized that younger OWTSs (e.g., ≤ 10 years) may exhibit signs of hydraulic failure at similar rates to older systems (e.g., >50 years). For instance, new homeowners may not be aware of the water loading limitations of their OWTS drainfield and overload the system. Additionally, soil compaction or clay smearing during drainfield installation, which results in lower water acceptance rates, is a commonly cited potential issue with newly installed drainfields (Jarrett et al., 1985; Noss and Billa, 1988; Swann, 2001; US Environmental Protection Agency, 1993). Over time, OWTSs may be expected to fail due to system deterioration and soil clogging. A quadratic age term would allow the model to detect higher incidences of maintenance at either end of the dataset's age distribution, while moderately aged systems might be expected to have lower maintenance rates when compared to these temporal extremes. In our candidate models, we used three important soil features that county health inspectors in the state of Georgia use for approving OWTS installations. We only tested these variables in combination because we hypothesized that these predictors together contributed to documented OWTS repair and pumping patterns and that no single soil condition was likely to drive these patterns. Models were evaluated and weighted using both the Bayesian information criterion (BIC) and Akaike information criterion (AIC) methods. However, only BIC was used for final model selection, as this method consistently provided better model discrimination and was also preferred due to the tendency of this method to favor parsimony in large datasets (Aho et al., 2014). Top performing models were verified for discrimination performance using the area under the receiver operating characteristic curve (AUC) calculation. Semivariogram plots and residual maps were used to assess spatial autocorrelation and residual clustering in candidate models with the highest BIC weights.

We also evaluated how anomalous pumping in OWTSs might be indicative of necessary repairs using logistic regressions between recent repairs and anomalous pumping. To do this, we restricted the date range of the repair dataset to five years prior to the earliest pumping record (January 2012) and assessed this model's performance based on its *p*-value. We also identified the number OWTSs with pumping events that were subsequently followed by a repair event. Due to the short temporal overlap of the pumping and repair datasets (January 2017 – March 2018) we did not specify a date lag between pumping and repair event (i.e., all OWTSs that met these conditions were included in the subset). All statistical analysis was conducted in the R statistical environment (R Core Team, 2020).

3. Results

The installation dates for OWTSs with high location confidence (n = 8826) ranged from January 1940 – March 2018. The median age of OWTSs in the county was 35 years. The median age of OWTSs in the repair dataset (n = 8786) was also 35 years, whereas the median age of repaired OWTSs was 65 years. The median age of OWTSs in the pumping dataset (i.e., OWTSs with high location confidence and specified capacities; n = 7676) was slightly younger, at 33 years, and the median age of a pumped system was 34 years. On average, approximately 0.5 % of the 8826 OWTSs in the study area were pumped per month over the 38-month period. December of 2018 was the month with the highest percent of pumping (0.8 %), and September of 2019 had the lowest single-month proportion of pumping (0.2 %). Additional summary statistics are detailed in Table 2.

3.1. Repair and pumping analyses

Repair records existed for 690, or 7.8 %, of the 8826 OWTSs with high location confidence. Though candidate models that included distance to the

Table 1
Response variables and candidate models for the repair, pumping, and anomalous pumping analyses[a].

Response			Candidate models[b]
Repair	Pumping	Anomalous pumping	
X	X	X	AGE
X		X	AGE + AGE^2
X	X	X	DIST.S
X	X	X	TWI
X	X	X	AGE + DIST.S
X	X	X	AGE + TWI
X	X	X	AGE + DIST.S + TWI
X	X	X	AGE + KSAT + DEP.R + DEP.WT
X	X	X	AGE + KSAT + DEP.R + DEP.WT + TWI
X[c]			Anomalous Pumping

[a] The presence of anomalous pumping was also used as a predictor of recent repairs. "X" indicates the candidate models that were tested to predict each of the three response variables. Variable abbreviations are also used in Table 3.

[b] AGE = Years since OWTS installation; AGE^2 = Quadratic age of OWTS; DIST.S = Distance to National Hydrography Dataset Plus flowline; TWI = Topographic wetness index; KSAT = Saturated hydraulic conductivity; DEP.R = Depth to restrictive layer; DEP.WT = Depth to seasonal water table.

[c] Repairs in this analysis were restricted to five years prior to the earliest pumping record.

Table 2
Summary statistics for OWTSs in Athens-Clarke County, Georgia[a].

Summary statistic	Value	Units
Median age of OWTSs in county	35	years
Median age of OWTSs in repair dataset	35	years
Median age of repaired OWTSs	65	years
Percent of OWTSs repaired[b]	7.8	percent
Median age of OWTSs in pumping dataset	33	years
Median age of pumped OWTSs	34	years
Percent of OWTSs pumped[b]	12.2	percent
Average volume of an individual pump	1202	gallons
Percent of systems pumped annually[b,c]	5.7	percent
Percent of pumping events which resulted in volume exceedances[b]	43.4	percent
Percent of OWTSs which had volume exceedances[b]	6.5	percent
Percent of OWTSs which were pumped more than once[b]	2.5	percent
Total volume of septage pumped in 38 months	1,933,307	gallons
Average monthly volume of septage pumped in the county	57,196.5	gallons

[a] The size of each respective dataset used to calculate these statistics can be found in Fig. 1.

[b] Percent of OWTSs out of the 8826 OWTSs with high location confidence (see Fig. 1).

[c] Percent calculated using monthly averages over a 38-month period of pumping records, multiplied by 12.

Table 3
Top performing models per response, as assessed by their Bayesian information criterion (BIC) weight[a].

Response		Model	β	95 % CI		BIC Weight	AUC
				Lower	Upper		
Repair		AGE	0.019	0.014	0.024	0.81	0.589
Pumping		Null	–	–	–	0.90	–
Anomalous pumping	Frequency	Null	–	–	–	0.81	–
	Volume	AGE + AGE^2	0.004; 0.002	−0.006; 0.001	0.014; 0.003	0.99	0.576
	Either	Null	–	–	–	0.69	–

[a] All model BIC weights per response are available in Supplementary Materials 2. Abbreviations as in Table 1.

nearest stream, TWI, and the three soil variables had low BIC weights, we found that OWTS age alone was a good predictor of whether a system was repaired (Table 3). This model identified incidents of OWTS repairs slightly better than a random model (AUC = 0.589). No spatial autocorrelation was present in this model's residuals (Supplementary Materials 1).

There were 1605 pumping manifests from 1076 OWTS tanks, meaning 12.2 % of the 8826 OWTSs were pumped in 38-months (an annualized rate of 5.7 %). Of these manifests, 697 of 1605 reported volumes greater or equal to the tank volume. We identified anomalous pumping for 638 OWTSs of the 1076 with manifest records, 218 of which were pumped two or more times per three years. The most frequently pumped OWTS was desludged 40 times. Additionally, 576 out of the 1076 OWTSs with pumping records had pumping events where the volume pumped was greater or equal to tank capacity (Fig. 2).

No candidate models in the pumping/no pumping analysis outperformed the null model (Table 3). Candidate models also failed to outperform a null model in the anomalous pumping analysis both for OWTSs that were frequently pumped and in the pooled frequently pumped or volume exceedance analysis. However, we found that a model with a quadratic age term performed well at predicting the occurrence of OWTS tanks with volume exceedance (Table 3; Fig. 3). This model indicates that tanks had a higher probability of pumped septage exceeding the installed tank capacity when they were either relatively new (2–10 years) or relatively old (>50 years). The top performing volume exceedance model identified positive incidences of this type of anomalous pumping slightly better than a random model (AUC = 0.576), although it should be noted that even this low AUC score is slightly optimistic because we validated our models with the same data we used to fit the models. No spatial autocorrelation was present in this model's residuals (Supplementary Materials 1).

After restricting the repair dataset by the date of the repair, 100 OWTSs were repaired during or five years prior to being pumped. Additionally, there was repair and anomalous pumping concurrence in 18 OWTSs, and we documented a weak, positive, statistical relationship in the logistic regression between repairs and anomalous pumping (β = 0.81, p = 0.106). Only 18 OWTSs were repaired between January 2017 and March 2018. Of these systems, five had a prerequisite pump, ranging from eight months to three days before the repair event.

4. Discussion

Decentralized wastewater treatment infrastructure is a critical component of water management in many regions of the US (US Census Bureau, 2020), and based on land development projections for suburban areas (Hamidi and Ewing, 2014; Homer et al., 2020), this is likely to remain true well into the future. Scientists and natural resource managers at the local (Walker et al., 2003), state (Macrellis and Douglas, 2009), and federal (US Environmental Protection Agency, 2005b) levels have highlighted the threats that poorly sited or maintained OWTSs present to human health and the environment. However, data describing relationships between OWTS characteristics, including age and edaphic conditions, and maintenance records, including pumping and repairs, are especially limited. Here, we used a county-wide dataset to assess relationships between site-level OWTS conditions and pumping and repair patterns. We found that OWTS age was a strong predictor of repairs and that older OWTSs were more likely to be repaired. Our analysis of OWTS anomalous pumping patterns suggests that both older systems, which are nearing the end of their service life, and newer systems that may have been improperly sited or designed, are most likely to exhibit signs of hydraulic failure. Our findings also suggest that widely available spatial data do not have high enough spatial resolution to capture environmental conditions at the drainfield scale. Collectively, our results indicate that younger OWTSs should be monitored for performance within the first few years of installation, while areas with older OWTSs should be targeted for sewer network expansion or proactive repair or replacement programs.

4.1. OWTS maintenance insights

4.1.1. System repairs

Our findings suggest that as an OWTS ages, it is increasingly likely to need repairs. This is supported by both empirical studies and anecdotal evidence. Using similar records, Noss and Billa (1988) calculated that OWTSs in Massachusetts had an expected half-life of approximately 25 years, though the probability of failure quickly increased after this age. The US EPA also reported an OWTS lifespan of 15 to 40 years (US Environmental Protection Agency, 2017), which is the age range of OWTSs in our dataset that were least likely to be repaired or show evidence of hydraulic failure. There is general agreement that OWTS monitoring,

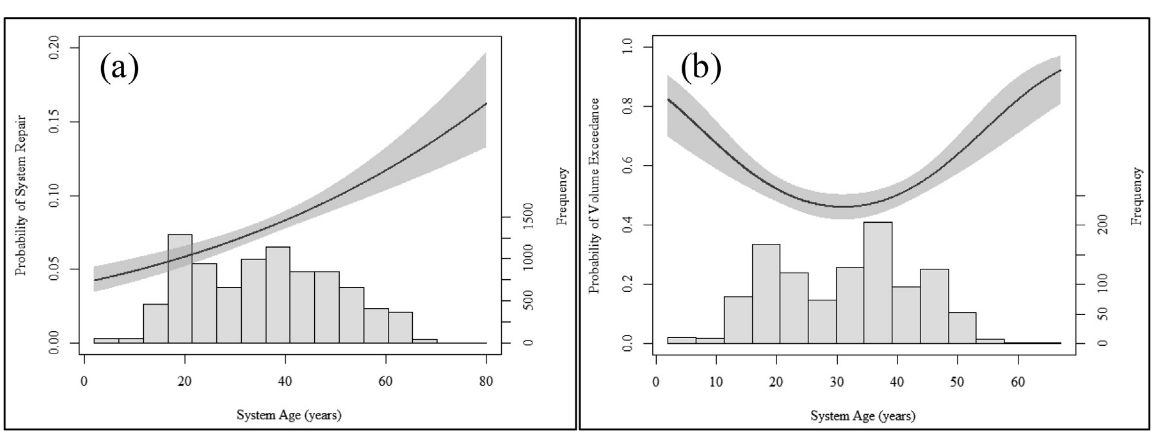

Fig. 3. (a) Probability of system repair per OWTS age (years between installation and October 2020), (b) probability of volume exceedance per quadratic OWTS age. Gray shading represents 95 % confidence intervals. Secondary y-axes indicate frequency of binned ages per analysis, which are displayed as underlying histograms.

maintenance, and replacement efforts should be focused on systems that are approaching the end of their service life (e.g., Georgia Department of Public Health, 2019a; Siegrist et al., 2000; US Environmental Protection Agency, 2005b). However, the realized lifespans of individual OWTSs are variable, so practitioners should develop objective performance definitions before implementing programs.

4.1.2. System pumping

The county's unique dataset of pumping records also provided valuable insights into how systems are maintained and when potential problems may arise. Unfortunately, we were unable to predict the occurrence of a binary pumping/no pumping response with our candidate models. There are several possible reasons for this. First, the resolution of spatial data may be insufficient to detect meaningful differences among sites, suggesting that the spatial predictors we used provide little insight into site-level OWTS management. Additionally, the socio-economic status of homeowners may play a role in pumping frequency (Flowers et al., 2019). Finally, homeowners may not know they have an OWTS or that regular maintenance is required (Goonetilleke and Dawes, 2001; Harrison et al., 2012). The annualized pumping rate of 5.7 % we documented in ACC is significantly lower than the rate of 11 % Silverman (2005) reported in a study of OWTS maintenance in northwest Ohio. In a similar study in Washington, 47 % of survey respondents indicated that their OWTS had been pumped in the last five years (Gomez et al., 1992). Due to the date range restrictions of the dataset we used, we are uncertain of the number of OWTS owners who serviced their systems in the preceding years. Local ordinances and community education programs likely contribute to some of these disparities in pumping rates. For example, the Douglasville-Douglas County, Georgia local government requires OWTSs built after 1991 in certain watersheds to be pumped every five years or the residence will be denied municipal water service (Frost, 1993). Such policies may result in increased local participation in regular OWTS maintenance and more frequent pumping.

4.1.3. Mechanisms of failure in OWTSs

To our knowledge, anomalous OWTS pumping, particularly in young systems (2–10 years), has not been previously reported. We posit three explanations for these unexpected results that indicate new OWTSs are nearly as likely as the oldest systems in the study to exhibit signs of hydraulic failure. Initially, the high failure rate of recently installed OWTSs may indicate poor placement or installation practices. In a study of OWTS drainfield function in North Carolina, Coulter et al. (1960) showed that over half of OWTSs on certain clayey soils failed within two years of installation. The researchers attributed these failures to the presence of a shallow impervious layer, poor surface drainage, or damage to the soils during installation. Collectively, this suggests that governments should improve training for personnel who oversee OWTS installation. Secondly, new homeowners may not know that system loading is limited by soil absorption rates. Education campaigns may help ameliorate some instances where lack of knowledge is a barrier to proper OWTS function. Lastly, the biologically active layer of soil directly below the drainfield (i.e., the biomat) changes rapidly within the first years of installation (Siegrist and Boyle, 1987). Soil clogging from fine particulates or elevated water loading can negatively affect biomat development and may result in reduced water acceptance rates (Siegrist, 1987). Any of these three system-level attributes may cause relatively new drainfields to become saturated and lead to system failure.

Some characteristics may contribute to volume exceedances in OWTSs of any age. The presence of garbage disposals can dramatically increase loading rates to OWTSs, which may expediate system clogging (Otis et al., 1980). Furthermore, some OWTSs may be undersized. In Georgia, OWTS construction guidelines rely on the number of bedrooms in a structure to make assumptions about water use. These approximated volumes are then used to determine the required size of the tank and drainfield (Georgia Department of Public Health, 2019b). If these assumptions underestimate water volume, drainfield overloading and system backup could result. We documented the expected pattern of increasing anomalous pumping with system age. This suggests that systems that had exceeded the recommended life expectancy of OWTSs (in this study >50 years) may be failing because of component deterioration and the reduction in absorption rates due to soil clogging over time.

Our data indicate there was a weak relationship between OWTSs that had anomalous pumping and were recently repaired, suggesting homeowners may be trying to address chronically failing systems through pumping. We speculate that these systems may have been sited inappropriately. In a survey of OWTSs on hydraulically sensitive soils in Connecticut, Groff and Obeda (1982) found that homeowners continued to experience signs of system failure, such as regular surface ponding, even after repair work was done. Owning an OWTS that concurrently exhibits signs of failure, and results in anomalous pumping, and also necessitates repairs, could be very costly. Data on OWTS repair expenses in Colorado showed that 60 % of repairs had an average cost of $14,866 per event (Kohler et al., 2016b), while regular pumping usually costs several hundred dollars per event (US Environmental Protection Agency, 2017). Many homeowners may not have enough resources to support these costs, and homeowners may be forced to address system failure through less expensive and less effective means. Our analysis only captures a subset of OWTSs where owner(s) have invested substantial capital into both pumping and repairs, and more data are needed to examine relationships between system failure and pumping frequency.

4.2. Socioeconomic and demographic considerations

The socioeconomic status of OWTS owners may also contribute to many of the pumping and repair phenomena we report in this study. As previously mentioned, the cost of OWTS maintenance can be economically prohibitive for many people, even when they know their system is failing. Our data indicate that in ACC, older systems are more likely to be repaired and are approximately equally as likely to exhibit signs of hydraulic failure as young systems. This finding may be relevant to class and racial divides in housing. Using a long-term, nationally-representative dataset of pre-retirement Americans, Flippen (2004) found that on average, African Americans are more likely to own older houses. Previous work has documented that older OWTSs are disproportionately located in predominately non-white and/or impoverished census blocks in ACC (Capps et al., 2020). Hence, the deleterious effects of failing OWTSs may be impacting vulnerable communities to a greater degree than what is currently recognized. Future work should couple demographic data with wastewater infrastructure to provide insights into community resilience and identify areas where environmental justice concerns need to be addressed.

5. Conclusions

Municipal governments throughout the US are challenged to manage decentralized wastewater infrastructure with relatively limited information. With a national median housing age of 37 years (American Society of Civil Engineers, 2021) and the understanding that only a small portion of malfunctioning OWTSs are ever repaired or replaced by homeowners (Gomez et al., 1992; US Environmental Protection Agency, 2002), it is very likely that aging and obsolete OWTSs are commonplace. However, ACC is unusual in that it has invested in a robust and continually updated dataset of OWTS locations and maintenance. Using a new approach to assess OWTS condition, we demonstrated how jurisdictions may leverage existing workflows to develop spatially and temporally explicit records of OWTS locations and pumping histories. Notably, there are still many unknowns in the ACC data. For instance, we have only a portion of the documented incidences of repairs, and we cannot quantify the number of OWTSs that need repairs but have not received any work. The analysis of volume exceedance pumps in this study is indicative of hydraulic failure. However, these records do not provide insight about drainfield failures where groundwater or surface water contamination is likely. Further site-specific assessments would be needed to identify the characteristics of OWTSs that are failing to completely treat wastewater.

Our findings indicate the oldest OWTSs (> 50 years) have the highest probabilities of repair. Notably, the newest OWTSs (2–10 years) were nearly as likely as the oldest systems to exhibit signs of hydraulic failure. Thus, policies that support OWTS repair and replacement should target older systems that are at or near the end of their serviceable life, while monitoring efforts should focus on all OWTSs one year after installation and on the oldest OWTSs. Our analysis also identified a markedly low OWTS pumping rate during the period of record. Regulations to monitor and incentivize specific OWTS management outcomes, such as more robust installation guidelines and appropriate pumping intervals (Goehring and Carr, 1980; Noss and Billa, 1988), may lead to increased homeowner participation in regular OWTS maintenance. Education initiatives are also relatively inexpensive and though the effectiveness of outreach programs alone to change homeowner behavior is likely low (Silverman, 2005), these programs can be used to notify homeowners when their OWTS is due for maintenance or inspection. By tracking and georeferencing OWTS maintenance activities, managers will be better informed to implement monitoring programs and address the externalities that are introduced by malfunctioning OWTSs. Focusing efforts on both newly installed OWTSs as well as aging ones may help practitioners identify systems that are not functioning adequately and guide decision makers in prioritizing wastewater infrastructure investments and policies.

CRediT authorship contribution statement

Kyle N. Connelly: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Seth J. Wenger:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Nandita Gaur:** Methodology, Writing – review & editing. **Jacob M. Bateman McDonald:** Methodology, Writing – review & editing. **Mike Occhipinti:** Investigation, Resources, Data curation. **Krista A. Capps:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration.

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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