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Onsite Wastewater System Nitrogen Contributions to Groundwater in Coastal North Carolina

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Abstract

The objective of the study described in this article was to evaluate the nitrogen contributions from two onsite wastewater systems (sites 1 and 2) to groundwater and adjacent surface waters in coastal Beaufort County, North Carolina. Groundwater levels and water quality parameters including total nitrogen, nitrogen species, temperature, and pH were monitored from October 2009 to May 2010. Nitrogen was also tested in groundwater from deeper irrigation or drinking water wells from the two sites and six additional neighboring residences. Mean total nitrogen concentrations in groundwater beneath onsite wastewater systems 1 and 2 were 34.3 ± 16.7 mg/L and 12.2 ± 2.9 mg/L, respectively, and significantly higher than background groundwater concentrations (<1 mg/L). Groundwater in the deeper wells appeared not to be influenced by the onsite systems. Groundwater nitrogen concentrations typically decreased with distance down-gradient from the systems, but were still elevated relative to background conditions more than 15 m from the systems and near the estuary. This was a pioneering effort to better understand the link of onsite systems, the fate of nitrogen in the environment, and public health.

Introduction

Excess nitrogen concentrations in surface waters and eutrophication continue to be a problem for many North Carolina watersheds (North Carolina Division of Water Quality, 2010). Approximately two million onsite wastewater treatment systems (OWS) are in North

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Carolina, and 40,000 OWS are installed annually (Hoover, 2004). Total dissolved nitrogen (TN) concentrations in OWS effluent typically range between 33 and 171 mg/L, with dissolved organic nitrogen (ON) and ammonium-nitrogen (NH_4^+-N) as the dominant nitrogen species (Water Environment Research Foundation [WERF], 2009). If OWS drainfield trenches are installed in aerobic soils with sufficient separation from the water table, effluent NH_4^+-N can be converted to nitrate-nitrogen (NO_3^--N) via the nitrification process (Humphrey, O'Driscoll, & Zarate, 2010). Anions like NO_3^--N are susceptible to leaching and contaminating the groundwater because most soils have a slight negative charge (Brady & Weil, 2004). The U.S. Environmental Protection Agency set the maximum contaminant levels (MCL) for NO_3^--N in ground and surface waters at 10 mg/L. Risks for methemoglobinemia in infants (blue-baby syndrome) are greater when water supplies exceed this MCL for NO_3^--N (U.S. Environmental Protection Agency, 2002). Shallow groundwater NO_3^--N concentrations adjacent to OWS can exceed 10 mg/L, especially in areas with sandy soils and deep water tables (Humphrey et al., 2010). Therefore, OWS must be installed at sufficient distances away from wells and surface waters to allow for possible nitrogen concentration reduction by such processes as denitrification, dilution, and dispersion. North Carolina regulations (15A NCAC 18A .1950d) require at least a 15–30 m setback distance from OWS to surface waters and wells. If nitrogen concentrations derived from OWS remain elevated in groundwater beyond the setback distances, the environment and public health may be compromised due to possible contamination of water supply wells, eutrophication of surface waters, and the potential exposure of the public to those waters.

Approximately 25% of North Carolina residences rely on private groundwater wells for their water supply, and 50% use OWS for wastewater treatment (North Carolina Conservation Network, 2010; Pradhan, Hoover, Austin, & Devine, 2007). A study conducted in eastern North Carolina in the early 1990s found that 25% of domestic wells tested had NO_3^--N concentrations that exceeded 10 mg/L; while agriculture was the most likely source of NO_3^--N, proximity to OWS was identified as a potential factor in the contamination (Stone, Novak, Jennings, McLaughlin, & Hunt, 1995). Findings of that study indicated that levels of NO_3^--N often exceeded the MCL in water of shallow wells (<30 m), but the MCL was not exceeded in water of deeper wells.

While the MCL for NO_3^--N is set at 10 mg/L, surface water concentrations of NO_3^--N or NH_4^+-N an order of magnitude less may stimulate algal blooms and eutrophication, which have been problematic in North Carolina and other regions of the U.S. (Fear, Gallow, Hall, Loftin, & Paerl, 2004; Patel, Pederson, & Kotelnikova, 2010). Thus our study objective was to evaluate the fate and transport of nitrogen derived from OWS for two residences in Beaufort County, North Carolina. More specifically, the goal was to determine whether OWS were impacting shallow groundwater, deeper groundwater used as a water supply or irrigation source, and adjacent surface waters. On the basis of prior research, we hypothesized that elevated nitrogen levels exist beyond the 15 m setback.

Methods

Site Instrumentation and Water Table Monitoring

Two volunteered residential sites in coastal Beaufort County, North Carolina, were selected for our study because of their close proximity to the nutrient-sensitive waters of the Tar-Pamlico estuary (Figure 1) and the presence of water supply or irrigation wells on site or in their respective neighborhoods. The OWS at sites 1 and 2 were both conventional gravity systems with a 3,780-L septic tank, distribution box, and three drainfield trenches, each approximately 15 m in length. Two occupants lived at site 1 and three occupants lived at site 2.

OWS components, including the septic tanks and drainfield trenches, were located by use of tile drain probe rods. The orientation of the septic plumes was estimated by use of an OhmMapper TR1 electrical resistivity mapper and the direction of groundwater flow was estimated on the basis of the hydraulic gradient as determined from a three-point problem solution at each site (Heath, 1998; Humphrey, Deal, O'Driscoll, & Lindbo, 2010). Piezometers were installed up- and down-gradient of the OWS flow paths for groundwater sample collection and monitoring (Figures 2 and 3). Bimonthly water table depths were determined manually by use of a Solinst model 107 temperature level and conductivity meter. Automated water level loggers were installed in piezometers near the drainfield disposal trenches, and they were programmed to record water levels every 0.5 hours. The automated water level measurements were used to observe temporal vertical separation distance (trench bottom and water table) dynamics. A YSI 556 field meter was used to determine groundwater and septic tank pH levels.

Two predominate soil series were at site 1 including soils similar in characteristics to the Tarboro sand (Mixed, thermic Typic Udipsamments), and Seabrook loamy sand (Mixed, thermic Aquic Udipsamments) (U.S. Department of Agriculture [USDA], 1995). The Seabrook soils have seasonal high water table depths typically within 1.2 m of the surface and were located at the beginning of the drainfield trenches and between the OWS and the estuary. The Tarboro soils are better drained and were located at the distal ends of the drainfield trenches and further from the estuary. Both soil series are sandy and have extremely permeable subsoils (>15 cm/hr) (USDA, 1995). The predominate soil series at site 2 was also Tarboro sand. Soil samples were collected from sites 1 and 2 for laboratory analysis including effective cation exchange capacity (ECEC).

Sampling Procedure

Septic tanks were sampled monthly from October 2009 to May 2010, and groundwater samples from piezometers and surface water samples from the estuary were collected bimonthly from November 2009 to May 2010. Wells for drinking water or irrigation were sampled monthly from the two sites, and from November 2009 to January 2010 samples from six additional neighboring residences were collected for the purpose of assessing the potential effects on other adjacent wells.

A new bailer was used for collecting groundwater samples from each piezometer. Piezometers were purged prior to sampling. Water samples were analyzed for pH and temperature by use of the YSI and Solinst field meters. Samples were kept on ice and delivered to the East Carolina University Central Environmental Laboratory within 12 hours where they were filtered prior to nitrogen analyses. Ammonia was analyzed by use of the Solorzano method (Eaton, Clesceri, & Greenberg, 1995). Kjeldahl nitrogen and nitrate/nitrite were analyzed by use of the Smart Chem 200 method.

Statistical Comparison Groups

Concentrations of TN in septic tank effluent were compared to those of groundwater beneath the OWS trenches to assess the effectiveness of these systems in reducing TN concentrations before discharge to groundwater. Concentrations of TN in groundwater beneath the drainfield trenches were compared to TN levels in background groundwater and drinking/irrigation water from deeper wells to help assess the effects of OWS on shallow and deeper groundwater. Groundwater down-gradient and ≤15 m (horizontal distance) of OWS was compared to groundwater down-gradient and >15 m from systems to determine whether setback regulations were effective at reducing TN concentrations. The piezometers most influenced by the OWS and >15 m down-gradient were referred to as the “plume core.” Mann Whitney or Wilcoxon rank sum tests (Conover & Iman, 1981; Davis, 2002) were used to determine whether significant differences in TN existed between comparison groups because the sample sizes were small and the data did not show a normal distribution.

Results

Average septic effluent TN concentrations varied between the sites (83.9 ± 13.5 mg/L for site 1 and 59.6 ± 5.2 mg/L for site 2), but they were within the typical ranges (33 to 171 mg/L) for domestic wastewater reported in a recent study (WERF, 2009). Groundwater TN concentrations beneath the drainfield trenches were significantly ($p < .05$) lower than septic effluent concentrations (site 1: 34.3 ± 16.7 mg/L and site 2: 12.2 ± 2.9 mg/L), but the groundwater TN concentrations were still elevated when compared to background conditions (site 1: 0.7 ± 0.4 mg/L and site 2: 0.3 ± 0.1 mg/L) (Figure 4). Mean TN concentrations in groundwater beneath drainfield trenches at sites 1 and 2 were 59% and 80% lower, respectively, than septic effluent concentrations for their respective tanks. Concentrations of TN typically decreased with distance from the OWS. At site 1, groundwater within 15 m of the OWS had mean TN concentrations of 20.9 ± 20.1 mg/L, while groundwater >15 m from the OWS had TN concentrations of 3.1 ± 3.4 mg/L (Figure 4). At site 2, groundwater within 15 m of the OWS had mean TN concentrations of 10.8 ± 2.8 mg/L, while groundwater >15 m had mean TN concentrations of 3.6 ± 3.3 mg/L (Figure 4). At times, however, TN concentrations in groundwater samples >15 m from the OWS systems at both sites were greater than 7 mg/L (plume core) (Figures 4 and 5). In addition, the mean groundwater TN concentration at the shore of the estuary ~40 m from the OWS was elevated at site 1 (4.2 ± 5.5 mg/L) (Figure 4). Drinking water or irrigation wells for sites 1 and 2 and the six adjacent properties never had TN concentrations greater than 1 mg/L.

Significant variation in nitrogen speciation was found across the sites and for the different samples. ON and NH_4^+-N were predominant in septic effluent for both sites (Figure 5).

Groundwater beneath the drainfield trenches, down-gradient from the system, and in background groundwater had predominately ON, followed by NH_4^+-N and NO_3^--N at site 1 (Figure 5). Dominant forms of nitrogen in groundwater beneath the drainfield trenches and down-gradient were NO_3^--N, followed by ON and NH_4^+-N at site 2, while background groundwater was mostly ON, followed by NH_4^+-N and NO_3^--N (Figure 5).

At site 1, groundwater levels were within 45 cm (North Carolina separation distance for group 1 soils) of the bottom of the drainfield trench for most of the period of November 2009–March 2010, with several short periods when groundwater levels were above the bottom of the drainfield trench (trench flooding) (Figure 6). During late fall and winter, from November 2009 to the end of March 2010, the mean separation from trench bottom to water table at site 1 was 31 cm. The overall mean separation distance for the study period at site 1 was 44 cm. At site 2, groundwater levels were much deeper, except for a few days when the water table rose after heavy rain events (Figure 7). The mean separation over the entire study period at site 2 from trench bottom to water table was 91 cm, more than twice the mean separation distance relative to site 1. From November to March 2010, the mean separation was 83 cm at site 2.

Mean water temperatures were highest for septic effluent at both site 1 (17.7 ± 4.2°C) and site 2 (19.3 ± 3.2°C) (Table 1). All other groundwater samples had similar mean temperatures with a range from 15.3 ± 3.7°C for groundwater beneath the site 1 drainfield to 16.7 ± 4.7°C for groundwater adjacent to the estuary at site 2 (Table 1). Mean pH levels were all slightly acidic and relatively similar, ranging from 5.5 ± 0.3 for the site 2 background groundwater to 6.8 ± 0.9 for the site 2 irrigation well water. The mean pH levels at site 1 ranged from 5.9 ± 0.5 (groundwater >15 m from the system) to 6.5 ± 0.9 (background groundwater) (Table 1). The soil analysis indicated that the ECEC of the Tarboro and Seabrook soils was less than 2 cmol/kg (centimoles of charge per kilogram of soil).

At site 1, the groundwater level data suggested that the predominant groundwater flow direction was to the south, towards the estuary. Water table data at site 2 suggested that the direction of groundwater flow is predominately from east to west across the site, but the direction may shift seasonally in response to significant recharge events and water table elevation variations.

Discussion

Onsite systems at sites 1 and 2 were both contributing elevated concentrations of nitrogen to shallow groundwater beneath the systems. The site 1 OWS was less efficient at reducing TN contributions to groundwater than the site 2 OWS, possibly because of a smaller separation from the water table and less potential for nitrification and denitrification processes (Figure 6).

Aerated soil beneath drainfield trenches is needed to provide conditions necessary for nitrification, a necessary precursor to denitrification. At site 1, the mean water level was within 45 cm of the trench bottom, and the dominant groundwater nitrogen species beneath the drainfield were NH_4^+-N and ON. Inhibition of nitrification has been reported for systems in sandy soils with less than 45 cm separation from the water table (Humphrey et al., 2010). Site 2 had a larger separation from the water table (mean = 91 cm), and the dominant groundwater nitrogen species beneath the drainfield was NO_3^--N; thus, nitrification was not inhibited at site 2.

Groundwater TN concentrations decreased further away (>15 m) from both systems, indicating dilution or other concentration reduction processes. While shallow groundwater TN concentrations were elevated, drinking/irrigation water samples from deeper wells had much lower TN concentrations (all <1 mg/L) and did not seem to be affected by the systems. An aquitard (confining layer) was discovered at site 2 approximately 5 m below the surface. This aquitard may have promoted lateral, rather than vertical, movement of groundwater, thus preventing deeper groundwater contamination (Stone et al., 1995).

At site 1, elevated TN concentrations were found adjacent to the estuary and down-gradient from the onsite system. Therefore, groundwater discharge to the sound, with elevated TN from the OWS, seemed likely. At site 2, the dominant form of nitrogen beneath the drainfield trenches and down-gradient from the system was NO_3^--N, showing the mobility of NO_3^--N in groundwater, a trait referenced by many other studies (Aravena & Robertson, 1998; Harmon, Robertson, Cherry, & Zanini, 1996; Robertson, Cherry, & Sudicky, 1991). The dominant form of nitrogen beneath the drain-field trenches and down-gradient from the OWS at site 1 was ON, indicating that ON was also mobile in the groundwater system. This is an important finding because unlike groundwater NO_3^--N, which may denitrify in organic-rich sediments adjacent to surface waters (Robertson et al., 1991), groundwater ON will not denitrify in sediments before discharge to the estuary and thus may contribute to the surface water TN loading. Prior studies have also indicated the mobility of OWS-derived ON or NH_4^+-N in groundwater down-gradient from systems (Carlile, Cogger, Sobsey, Scandura, & Steinbeck, 1981; Corbett, Dillon, Burnett, & Schaefer, 2002). The research sites for our study are located in the Tar-Pamlico River Basin, where the Nutrient Sensitive Waters Management Strategy (15A NCAC 2B) calls for a reduction in the TN loading to the river. Thus OWS may be a TN-loading source via groundwater transport of organic and ammonium nitrogen.

Study Limitations

The main limitation of our study was funding, which impacted on the number of sites that were included. A representative sample size would have allowed drawing conclusions applicable to other OWS in the coastal region of North Carolina where the study took place.

Conclusion

Our study has been a pioneering collaborative effort to better understand the potential link of OWS, the fate of nitrogen that could be applied to this coastal setting, and public health. Nitrogen derived from OWS can impact shallow groundwater beneath OWS and adjacent surface waters. ON and NO_3^--N were found at the sites, which indicate that speciation is needed when accounting for the fate of nitrogen in the environment. Levels of NO_3^--N beyond state setback regulations can be higher than background levels. It appears that deeper groundwater is protected. More work is needed, however, and has been planned to better delineate waste-water plumes, quantify nitrogen speciation and attenuation processes, and discharge rates relative to existing required setback distances.

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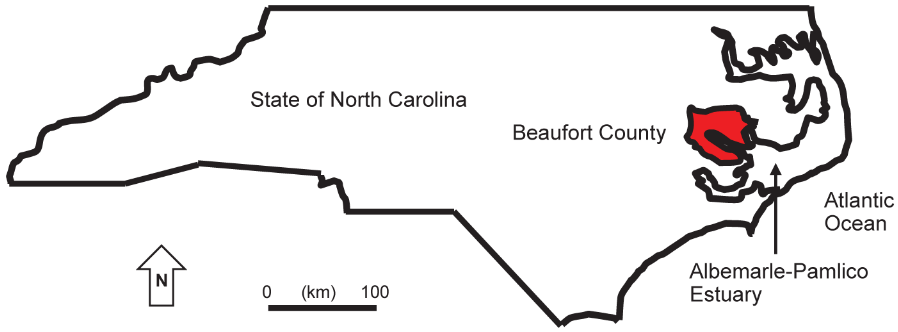

FIGURE 1. Research Location

Research sites were located in Beaufort County, North Carolina (shaded in red), within the Tar-Pamlico River Basin and adjacent to the Albemarle-Pamlico Estuary and Atlantic Ocean.

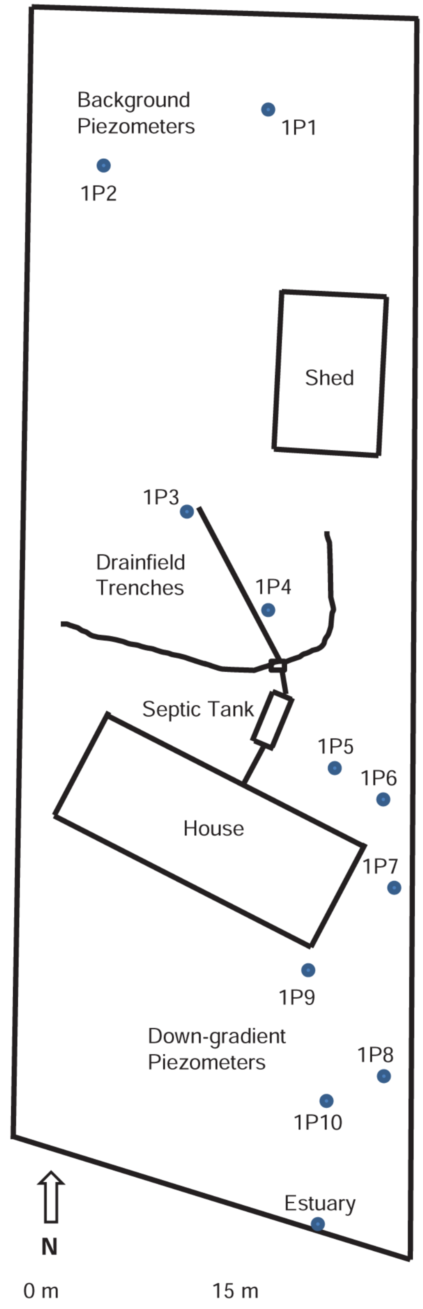

FIGURE 2. Site 1 Map

Showing onsite wastewater system components, piezometer locations, and the residence (1P1–1P10 indicate piezometers 1–10 at site 1).

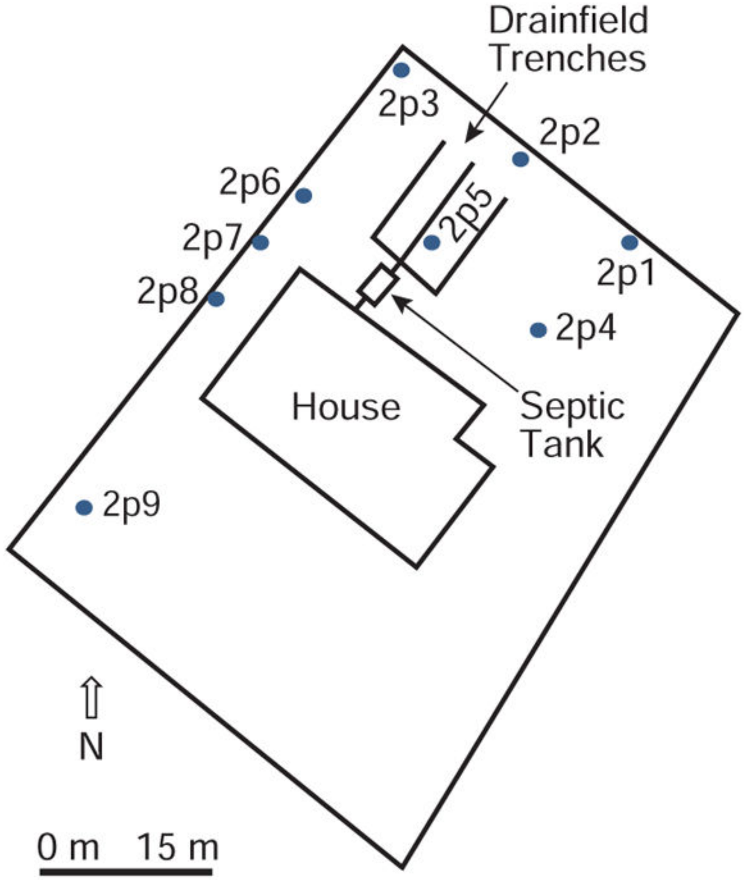

FIGURE 3. Site 2 Map

Showing onsite wastewater system components, piezometer locations, and the residence (2p1–2p9 indicate piezometers 1–9 at site 2).

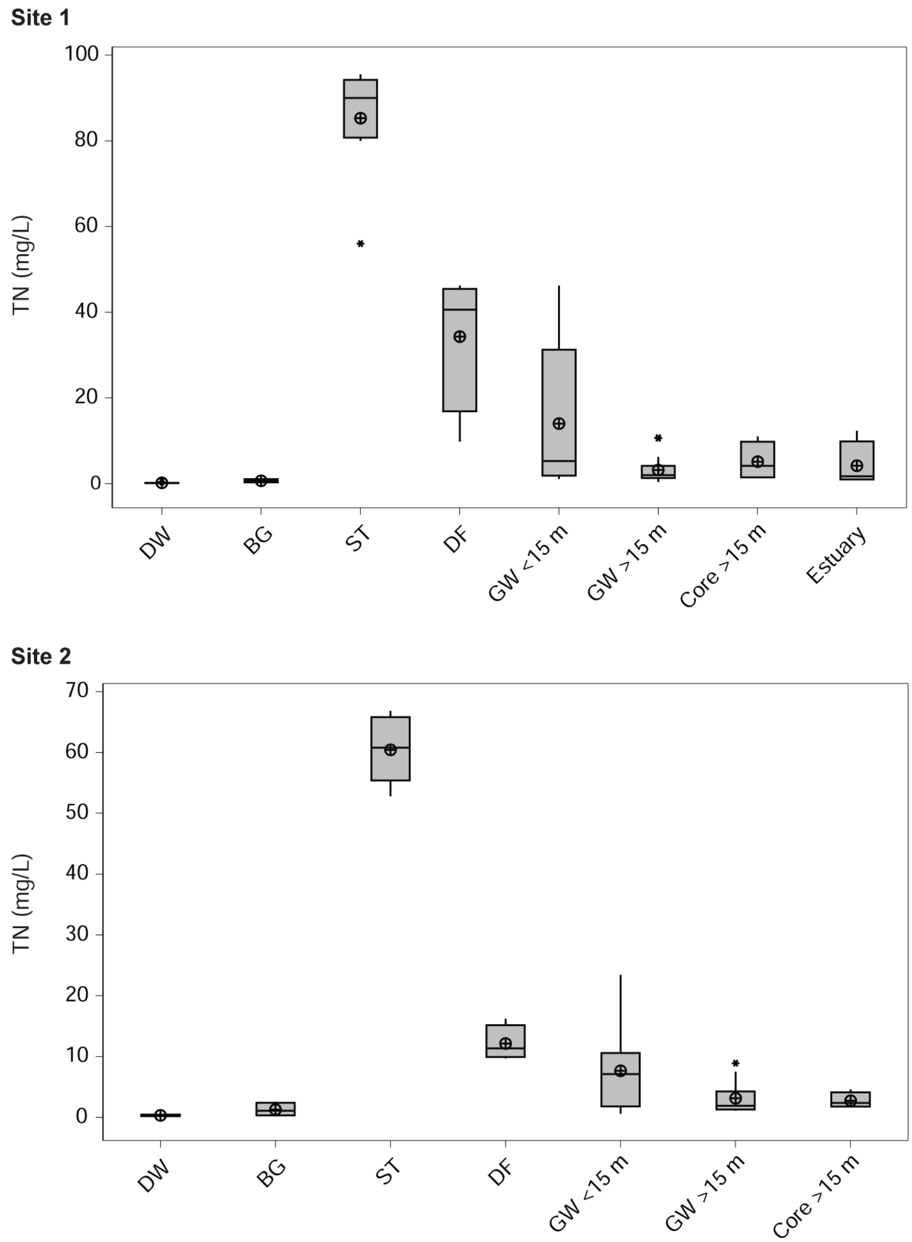

FIGURE 4. Total Dissolved Nitrogen (TN) Concentrations at Sites 1 and 2

Including drinking and/or irrigation wells (DW), background wells (BG), septic tanks (ST), groundwater beneath the drainfield trenches (DF), groundwater (GW) within 15 m (<15 m) of the onsite wastewater treatment system (OWS), groundwater more than 15 m (>15 m) from the OWS, plume core wells (Core), and the estuary.

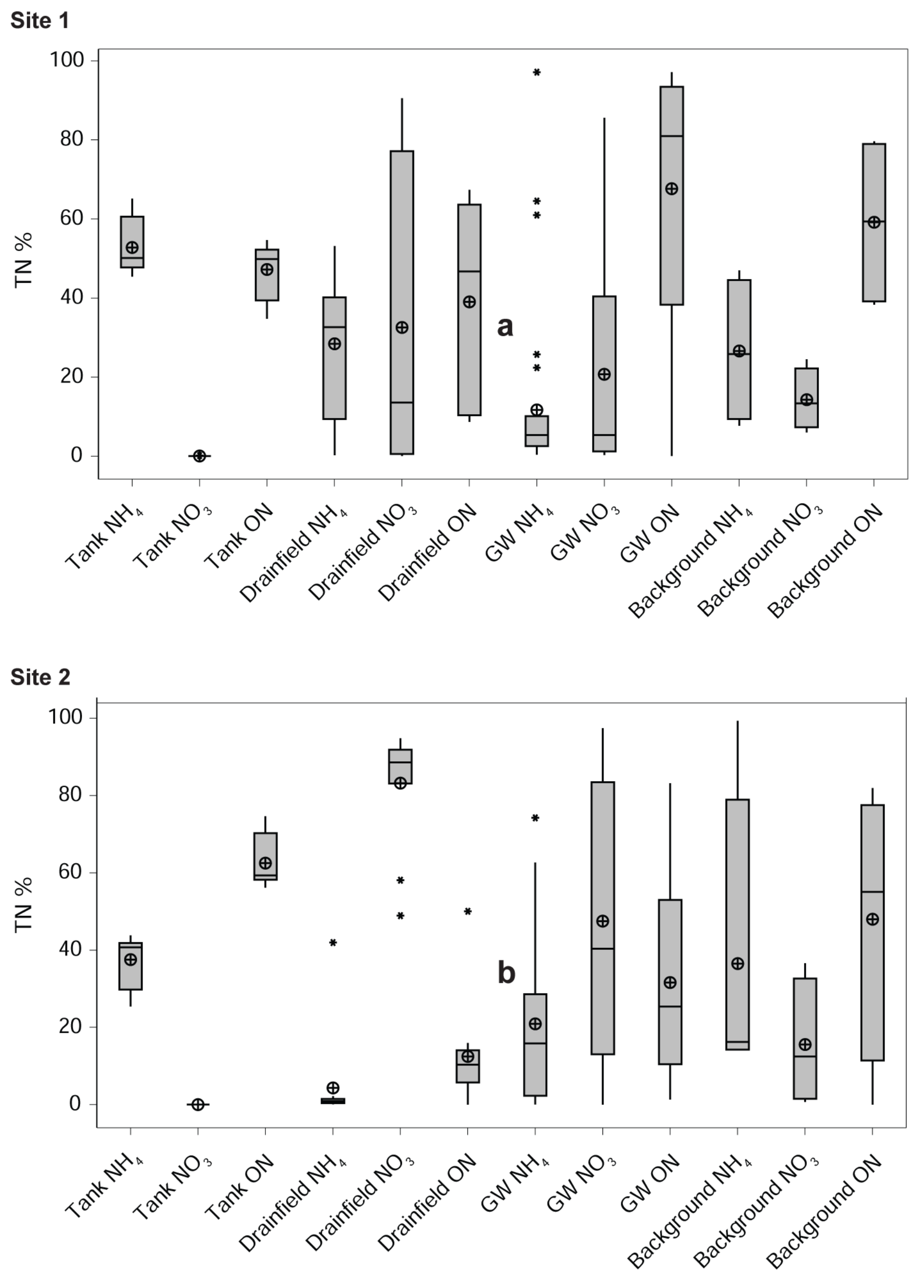

FIGURE 5. Nitrogen Speciation

Dissolved organic nitrogen = ON; ammonium = NH_4; nitrate = NO_3; TN = organic + NO_3 at sites 1 and 2 monitoring locations, including the tanks (Tanks), groundwater beneath drainfield trenches (Drainfield), groundwater down-gradient from the trenches (GW), and background groundwater (Background).

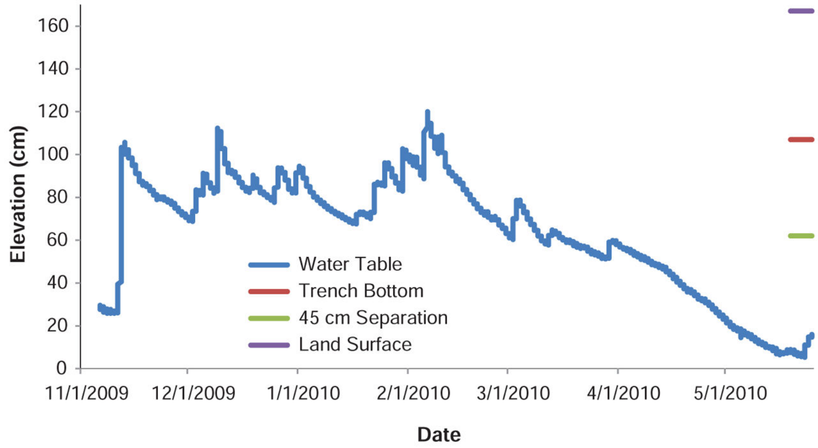

FIGURE 6.
Variation in Groundwater Elevation for Site 1, November 2009–May 2010

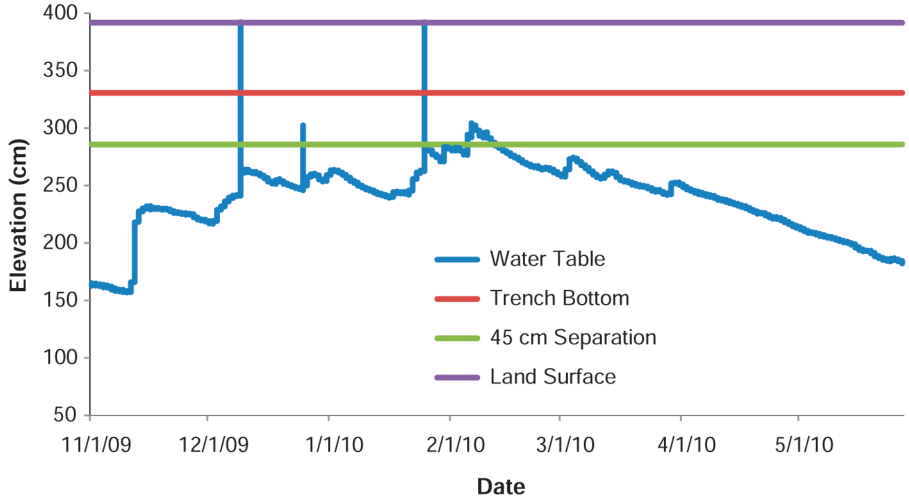

FIGURE 7.

Variation in Groundwater Elevation for Site 2, November 2009–May 2010

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TABLE 1

Temperature (°C) and pH Values for Site 1 and Site 2 Monitoring Locations

Site 1[a]	pH	Temperature	Site 2[a]	pH	Temperature
BG	6.5 ± 0.9	15.3 ± 4.2	BG	5.5 ± 0.3	15.6 ± 2.8
ST	6 ± 1	17.7 ± 4	ST	6.1 ± 0.7	19.3 ± 3.2
DF	6.1 ± 0.5	15.3 ± 4.3	DF	5.8 ± 0.6	15.4 ± 3.5
<15 m	6.2 ± 0.5	15.5 ± 3.7	<15 m	5.6 ± 0.7	15.6 ± 3.2
>15 m	5.9 ± 0.5	16.0 ± 3.2	>15 m	6.1 ± 0.7	15.4 ± 3.1
Est	6.1 ± 0.9	16.7 ± 4.7	Est	–	–
DW	6.1 ± 0.9	15.4 ± 3.7	DW	6.8 ± 0.9	16.2 ± 4.1

[a]BG = background groundwater; ST = septic tank effluent; DF = groundwater beneath the drainfield trenches; <15 m = groundwater within 15 m of drainfields; >15 m = groundwater further than 15 m from drainfields; Est = the estuary; DW = drinking/irrigation wells.