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Biogeochemistry of Groundwater beneath On-site Wastewater Systems in a Coastal Watershed

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Abstract:

The goal of this study was to determine if on-site wastewater system PO_4 and coliform contributions to groundwater were significant enough to be included in water quality management plans for a coastal watershed. Monitoring wells were installed adjacent to 16 on-site systems in three different soil types (sand, sandy loam and sandy clay loam) in Carteret County, North Carolina. Groundwater beneath on-site wastewater systems was collected and analyzed for coliform bacteria and PO_4 and compared to septic effluent and background groundwater. Physical and chemical properties of groundwater including pH, electrical conductivity, and temperature were measured monthly for over 1 year (January 2007-February 2008). Data indicated that mean groundwater pH, PO_4, coliform and electrical conductivity beneath on-site systems were typically elevated relative to background groundwater. Groundwater beneath on-site wastewater systems in sandy clay loam soils had the lowest mean PO_4 and lowest median coliform concentrations (0.04 ± 0.03 mg/L and 1.02×10^4 cfu/100 mL). On-site systems in sand had the highest mean groundwater PO_4 concentrations (2.46 ± 2.9 mg/L) and systems in sandy loam had the highest median groundwater coliform concentrations (2.21×10^4 cfu/100 mL). On-site wastewater systems in watersheds with sandy soils ($> 77\%$ sand and $< 24\%$ clay) can contribute significant concentrations of PO_4 and coliform to groundwater and these contributions should be included in watershed management strategies for improving water quality.

Keywords: Coastal watershed, coliform, phosphate, soils, wastewater

1.0 Introduction:

Many coastal areas of the United States including the Chesapeake Bay, Albemarle Pamlico Sound, and Buzzards Bay have experienced eutrophic conditions and/or closure of shellfisheries due to excess nutrient loads and bacterial pollution (Vailiela and Costa, 1988; Fisher *et al.,* 1992; Fear *et al.,* 2004; Cahoon *et al.,* 2006). While urban stormwater and agricultural runoff are often cited as major contributors of nutrients and microorganisms to coastal waters, wastewater discharges from centralized sewer plants and from on-site wastewater systems (OSW) to surface waters can also be significant (Valiela and Costa, 1988; Harris, 1995; Anderson *et al*., 2002; Cahoon *et al*., 2006). Domestic wastewater typically contains elevated concentrations of N and P, microbial organisms, heavy metals, and dissolved salts and solids (Ptacek, 1998; Alaboud, 2009; Daghrah and Al-Sa'ed, 2009; Water Environment Research Foundation, 2009; Humphrey *et al.,* 2010; Humphrey *et al.,* 2011). Some research has shown that OSW can contribute significant P concentrations to groundwater, creating extensive P-enriched plumes (Harmon *et al.,* 1996; Ptacek, 1998; Corbett *et al.,* 2002), while other studies concluded that OSW were very effective at reducing P concentrations prior to groundwater discharge (Carlile *et al.,* 1981; Reay 2004). Studies have also shown that OSW can contribute microorganisms to ground and surface waters in coastal environments (Lipp *et al.,* 2001; Booth *et al.,* 2003; and Cahoon *et al.,* 2006), but most of the mitigation efforts in North Carolina have focused on reducing stormwater runoff (NC Session Law 2008-211), agricultural runoff, and improving centralized sewer plant treatment efficiencies (North Carolina Department of Environment and Natural Resources, 2003). More information is needed regarding OSW phosphorous and microbial contributions to water resources to determine if OSW contributions should be considered in watershed-scale water quality management plans.

The goal of this research was to provide further insight into the impacts that OSW have on groundwater in coastal areas and determine if these impacts should be included in watershed scale management plans. Specific project objectives included: 1) evaluate the groundwater phosphate and coliform concentrations beneath OSW installed in soils typical of coastal environments and 2) characterize the physical and chemical properties of groundwater beneath the on-site systems including pH, temperature, and electrical conductivity.

2.0 Materials and Methods:

2.1 Site selection: Carteret County, North Carolina, United States of America was chosen as the study location because it is a coastal county within the nutrient sensitive, Albemarle Pamlico Estuarine System (Figure 1). Massive fish kills related to eutrophic conditions, numerous swimming advisories and the closure of shellfish waters have been common in the estuary (North Carolina Department of Environment and Natural Resources, 2003; Fear *et al.,* 2004; North Carolina Division of Water Quality, 2007). Sixteen residences across Carteret County were instrumented with 10 cm diameter PVC groundwater wells near the drainfield trenches (OSW) that served the homes. Wells were also installed up-gradient of the systems to provide background groundwater quality comparisons. Some neighboring sites shared a background well.

***2.2 Soil analyses*:** Soil samples were collected during the installation process for descriptive analyses including particle size distribution, soil color and effective cation exchange capacity (ECEC), and slug tests were used to determine the hydraulic conductivity of the saturated zone (Ksat). These sites, installation methods, and soil analyses were described in previous studies (Humphrey *et al.,* 2010; Humphrey and O'Driscoll, 2011).

2.3 Groundwater quality analyses: Groundwater physical and chemical properties including temperature, electrical conductivity and pH were determined monthly from January 2007 to February 2008, using a *YSI Sonde 6920* multi-parameter water quality meter and a *Solinst Model 107* Temperature Level and Conductivity (TLC) meter. Samples were collected from groundwater wells and septic tanks two to three times over the study period and analyzed for phosphate (PO_4) using procedures described in the *Standard Methods for Examination of Water and Wastewater* (1998). Groundwater samples were collected using new, disposable bailers, for each sample and samples were immediately place on ice in coolers for transport to the laboratory. Groundwater samples were analyzed seasonally (4 times) for total coliform using the membrane filtration method with *m-ColiBlue24 Broth* (Grant, 1997). Samples were incubated at 35° C for 24 hours, and the colonies counted and recorded. Tanks samples were analyzed three times for coliform during the study.

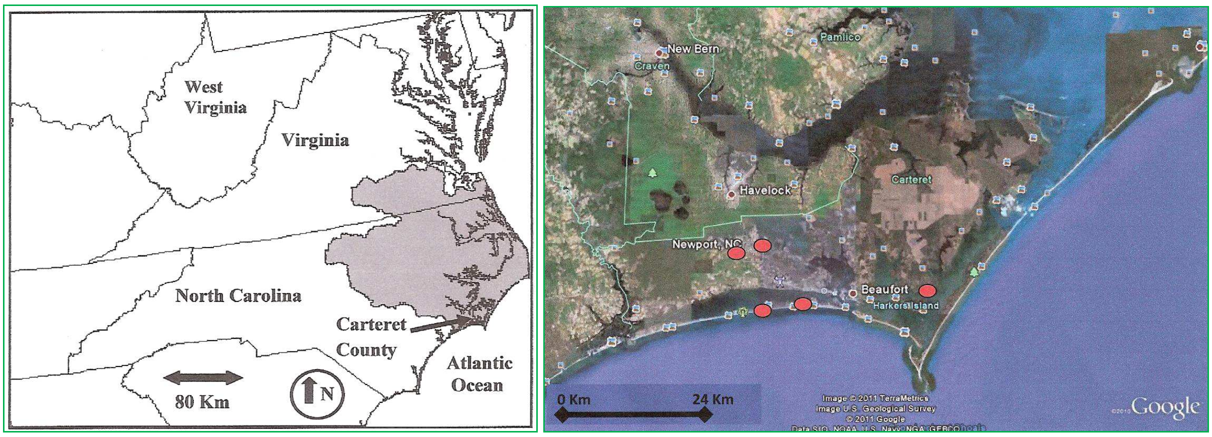

Figure 1. Albemarle Pamlico Sound Drainage Basin in North Carolina and Virginia, United States of America (shaded region of diagram). Research sites were located across coastal Carteret County, North Carolina (red circles on aerial view).

***2.4 Statistical comparisons*:** Groundwater physical and chemical properties, total coliform and PO_4 concentrations adjacent to the drainfields were compared to septic tank effluent and groundwater characteristics in background wells to determine the influence of OSW on groundwater properties. Groundwater total coliform and PO_4 concentrations beneath systems installed in sands were compared to groundwater beneath systems in sandy loam and sandy clay loam soils to determine if soil type influenced treatment. Data were also pooled for the different comparisons groups (all tank data compared to all groundwater beneath OSW data, compared to all background groundwater data) to determine the overall impact of OSW on groundwater. Mann Whitney non-parametric tests were performed using the statistical software *Minitab 16* to determine if significant differences were found between the comparison groups.

3.0 Results and Discussion:

3.1 Soil Properties:

Particle size analyses indicated that beneath the drainfield trenches 8 sites had sand, 4 sites had sandy loam and four sites had sandy clay loam textural classifications (Table 1). Sites with sand textural classifications beneath the drainfield trenches had the greatest mean hydraulic conductivity (13.92 cm/hr) and relatively low mean ECEC (3.1 cmol/kg) (Table 1). Sites with sandy clay loam textural classification had the lowest mean hydraulic conductivity (0.79 cm/hr), the highest mean ECEC (7.4 cmol/kg), and highest mean soil chromas colors (5.5) beneath the drainfield trenches (Table 1). Sites located on the barrier island towns of Pine Knoll Shores and Atlantic Beach had the highest % sand (all 97% +), highest Ksat values (5.71 to 35.17 cm/hr), lowest mean soil color chroma (2.8) beneath OSW, and low ECEC (mean of 2.9) (Table 1).

3.2 Septic Tank Effluent PO_4 and Coliform Concentrations:

Mean septic tank effluent PO_4 and median total coliform concentrations were 5.92 ± 2.57 mg/L and 1.75×10^7 cfu/100 mL, respectively (Figure 2 and 3). The PO_4 and total coliform concentrations for OSW in the three soil types were variable (sand 5.6 ± 1.67 mg/L and 2×10^7 cfu/100 mL; sandy loam 8.1 ± 2.57 mg/L and 1.53×10^7 cfu/100 mL; and sandy clay loam 3.4 ± 1.26 mg/L and 1.0×10^7 cfu/100 mL) but similar to concentrations reported in other research (Harmon *et al.,* 1996; Robertson *et al.,* 1998; US EPA, 2002; Alaboud and Magram, 2008; Alaboud, 2009) (Figure 2 and 3). Tank effluent from OSW in sandy loams soils (8.1 ± 2.57 mg/L) had significantly higher PO_4 concentrations than OSW effluent in sand (5.67 ± 1.67 mg/L) and sandy clay loam soils (3.4 ± 1.26 mg/L). Significant differences were not found between septic effluent PO_4 concentrations for OSW in sand and sandy clay loams soils. No significant differences were found when comparing septic effluent coliform concentrations for OSW in sand, sandy loam and sandy clay loam soils. Wastewater strength can be influenced by a number of factors including type of plumbing fixtures and appliances, lifestyle characteristics of the different families and system users, and water supply source (US EPA, 2002). These factors may explain the differences in effluent PO4 and coliform concentrations between the sites.

3.3 Groundwater Quality Beneath OSW In Different Soil Types:

Groundwater PO_4 and total coliform concentrations were lowest beneath OSW in sandy clay loam soils (0.04 ± 0.03 mg/L and 6.59×10^3 cfu/100 mL) (Figure 2 and 3). OSW in sand had the highest groundwater PO_4 concentrations (2.46 ± 2.92 mg/L) and second highest coliform concentrations (2.16×10^4 cfu/100 mL) while OSW in sandy loam had intermediate PO_4 concentrations (0.39 ± 0.45 mg/L) and the highest median coliform concentrations (2.21×10^4 cfu/100 mL) (Figure 2 and 3). Groundwater PO_4 concentrations beneath OSW in sand were significantly higher than groundwater PO_4 concentrations beneath OSW in sandy loam and sandy clay loam soils. Furthermore, groundwater PO_4 concentrations beneath OSW in sandy loam were significantly higher than groundwater PO_4 concentrations beneath OSW in sandy clay loam soils. Only groundwater beneath OSW in sands had significantly higher PO_4 (2.46 ± 2.92 mg/L) concentrations relative to background groundwater (0.10 ± 0.08 mg/L). Therefore, statistically significant differences were not found between PO_4 concentrations in groundwater beneath OSW in sandy loams (0.39 ± 0.45 mg/L) and background groundwater (0.48 ± 0.29 mg/L) or sandy clay loams (0.04 ± 0.03 mg/L) and background groundwater (0.05 ± 0.05 mg/L), indicating better treatment in these more fine textured soils (Figure 2). For OSW in sand and sandy clay loam soils, groundwater beneath OSW had significantly higher total coliform concentrations that background groundwater (Figure 3). Significant differences were not found when comparing groundwater beneath OSW in sandy loams and background concentrations, mostly due to elevated background concentrations (median 1.02 x 10^4 cfu/100 mL).

3.4 Physical and Chemical Properties:

The mean pH of septic effluent (6.6 ± 0.3) was similar to groundwater pH beneath OSW (6.7 ± 0.3) (Table 2). The pH of tank effluent and groundwater beneath OSW were significantly ($p < 0.05$) higher than background conditions (6.0 ± 0.5) indicating that OSW were influencing groundwater chemistry. Septic tank effluent pH values were similar for OSW in sand (6.5 ± 0.4), sandy loam (6.8 ± 0.1) and sandy clay loam (6.7 ± 0.1) soils (Table 2). No significant differences were found between effluent pH and groundwater beneath OSW in any of the soils.

Table 1. Soil properties beneath on-site wastewater trenches for each site including the particle size distribution (% sand/silt/clay), hydraulic conductivity (Ksat), effective cation exchange capacity (ECEC) and soil color (hue, value and chroma). (*) denotes mean for barrier island (Atlantic Beach and Pine Knoll Shores) sites.

Soil Properties Beneath OSW Trenches

Site ID	City/Town	% sand/silt/clay	Texture	Ksat (cm/hr)	ECEC (cmol/kg)	Soil Color
SI-A	Newport	90/5/5	S	4.08	5.6	10YR 4/6
SI-B	Newport	95/2/3	S	10.29	1.2	10YR 4/4
SI-C	Newport	91/4/5	S	4.21	3.2	10YR 4/4
SI-D	Atlantic Beach	98/0/2	S	8.13	2.3	10YR6/4
SI-E	Pine Knoll Shores	98/0/2	S	35.17	1.5	2.5Y 6/4
SI-F	Pine Knoll Shores	97/0/3	S	5.71	2	10YR4/4
SI-G	Pine Knoll Shores	98/0/2	S	23.75	5.6	2.5Y 5/1
SI-H	Pine Knoll Shores	97/1/2	S	20.08	3.1	10YR 3/1
Mean		**96/1/3**		**13.92**	**3.1**	**3.5 (2.8*)**
SII-A	Newport	74/10/16	SL	0.75	3.2	10YR 4/3
SII-B	Newport	81/10/9	SL	2.17	3.5	10YR 4/3
SII-C	Newport	79/8/13	SL	2.04	2.8	10YR 5/4
SII-D	Newport	75/11/14	SL	0.38	2.1	10YR 4/3
Mean		**77/10/13**		**1.33**	**2.9**	**3.3**
SIII-A	Smyrna	67/12/21	SCL	0.63	7	10YR 5/4
SIII-B	Smyrna	71/5/24	SCL	0.75	7.7	10YR 4/6
SIII-C	Smyrna	67/8/25	SCL	0.38	7.2	10YR 4/6
SIII-D	Smyrna	65/10/25	SCL	1.42	7.5	2.5Y 5/6
Mean		**67/9/24**		**0.79**	**7.4**	**5.5**

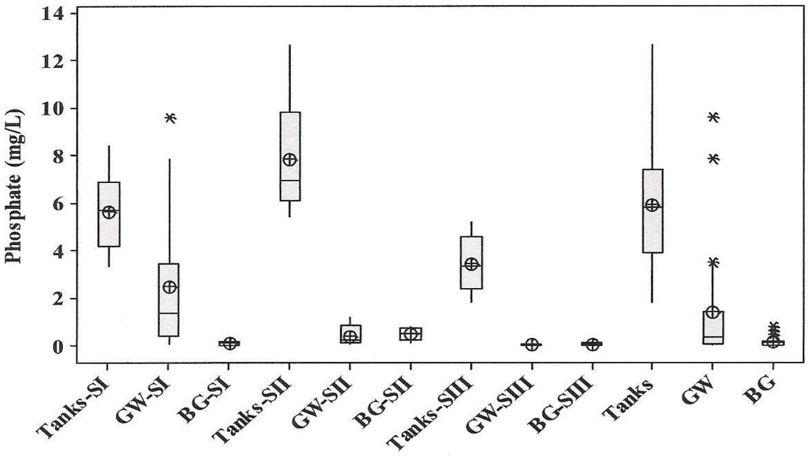

Figure 2. Phosphate concentrations for tanks, groundwater beneath drainfield trenches (GW) and background groundwater (BG) for sites with sand (SI), sandy loam (SII) and sandy clay loam (SIII) soils. Tanks, GW and BG are pooled data from all sites.

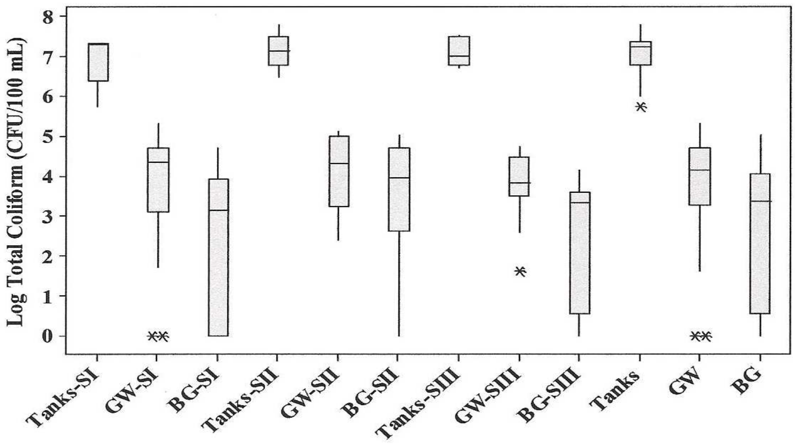

Figure 3. Log of total coliform concentrations (cfu/100 mL) in tanks, groundwater beneath drainfield trenches (GW) and background groundwater (BG) for sites with sand (SI), sandy loam (SII) and sandy clay loam (SIII) soils. Tanks, GW and BG are pooled data from all the sites.

While groundwater electrical conductivity was measured (Table 2), septic tank effluent was not measured. Research has shown that wastewater electrical conductivity is typically elevated and above 1200 uS/cm (Harmon *et al.,* 1996; Daghrah and Al-Sa'ed, 2009). Groundwater electrical conductivity beneath OSW in sand (560 ± 370 µS/cm), sandy loam (636 ± 782 µS/cm) and sandy clay loam soils (523 ± 251 µS/cm) were significantly higher than background groundwater for each soil type (sand 257 ± 183 µS/cm; sandy loam 109 ± 72 µS/cm; and sandy clay loam 301 ± 144 µS/cm). Because some sites were located adjacent to estuarine and/or marine waters, the electrical conductivity of the groundwater in those areas was more elevated than sites further inland, possibly because of the influence of the high salt content of nearby brackish and salt waters. Pooling all groundwater data, groundwater beneath OSW had significantly higher electrical conductivity (569 ± 484 µS/cm) than background groundwater (235 ± 170 µS/cm), thus indicating that OSW were influencing the physical properties of groundwater. Mean groundwater temperatures beneath OSW (18.8 ± 5.0 °C) and background groundwater (18.8 ± 4.6 °C) were similar, and no significant differences were found (Table 2).

Table 2. Average (± 1 standard deviation) groundwater pH, electrical conductivity, and temperature, beneath on-site wastewater systems (GW) in sand, sandy loam, sandy clay loam and all soils combined in comparison to background groundwater (BG).

Sands (SI)	**pH**	**Electrical Conductivity (µS/cm)**	**Temp (°C)**
SI-GW	6.7 (0.4)	560 (370)	20.2 (4.1)
SI-BG	5.8 (0.6)	257 (183)	19.5 (3.8)
SI- Tanks	6.5 (0.4)		
Sandy Loams (SII)			
SII-GW	6.6 (0.5)	636 (782)	18.1 (5.0)
SII-BG	6 (0.3)	109 (72)	17.9 (4.9)
SII-Tanks	6.8 (0.1)		
Sandy Clay Loams (SIII)			
SIII-GW	6.8 (0.4)	523 (251)	18.6 (4.9)
SIII-BG	6.6 (0.4)	301 (144)	18.2 (5.4)
SIII-Tanks	6.7 (0.1)		
All Soils			
GW	6.7 (0.3)	569 (484)	18.8 (5.0)
BG	6.0 (0.5)	235(170)	18.8 (4.6)
Tanks	6.6 (0.3)		

3.5 Overall Trends:

Pooling all data, groundwater beneath OSW typically contained higher mean PO_4 and total coliform concentrations and elevated electrical conductivity and pH relative to background groundwater. Therefore most OSW were influencing groundwater physical, chemical and biological properties. The highest groundwater phosphorous concentrations were found beneath OSW in sand, followed by sandy loam, and sandy clay loam soils. The highest total coliform concentrations were found beneath OSW in sandy loam, followed by sand, and sandy clay loam soils. This shows that OSW installed in soils with higher clay contents (sandy clay loams) were more effective at reducing phosphorous and total coliform concentrations than OSW in sandier soils. The sandy clay loam soils had lower hydraulic conductivities, higher mean soil color chroma beneath OSW trenches, and more reactive surface area (clay size fraction) than the other soils, possibly providing more time, opportunity and exchange sites for phosphorous adsorption and total coliform filtration (Gerba, 1984; Yates *et al.,* 1985; Havlin *et al.,* 1999; Karathanasis *et al.,* 2006a; Karathanasis *et al.,* 1996b).

3.6 Phosphate Treatment:

The geochemical processes that determine the movement of PO_4 in soils and aquifers beneath OSW include adsorption/desorption and precipitation/dissolution reactions (Harmon et al., 1996). Phosphate, an anion, can be adsorbed to positively charged natural surfaces of soil solids such as Fe (III) oxides and clay minerals (Ptacek, 1998; Havlin et al., 1999). Many of the sand soils in Carteret County, especially on barrier island towns such as Atlantic Beach and Pine Knoll Shores, formed from iron poor parent materials, lack iron coatings on sand grains, and exhibit low chroma colors (Buol *et al.,* 1997; Richardson and Vepraskus, 2001; Humphrey and O'Driscoll, 2011). The mean soil color chroma beneath OSW trenches in the barrier island towns (2.8) was the lowest of all locations. Because iron oxides provide sites for phosphorous adsorption (Ptacek, 1998; Havlin *et al.,* 1999), soils with low iron content may have less ability to retain phosphorous. Soils and aquifers with higher clay contents can provide significant PO_4 adsorption capacity at pH levels near neutral (Ptacek, 1998). The mean groundwater pH values beneath OSW in the different soil groups were near neutral (6.6 to 6.8).

This may explain why OSW in sandy clay loam soils had the lowest PO_4 concentrations in groundwater beneath the systems, followed by sandy loam soils, and then sands.

3.7 Coliform Treatment:

Prior studies have shown that the major coliform removal mechanism is filtration in aerated soil beneath drainfield trenches and bacteria can be transmitted further in coarse-textured soils relative to more clay rich soils (Gerba *et al.,* 1984; Yates *et al.,* 1988; Karathanasis *et al.,* 2006b). The OSW in sandy clay loam soils in this study performed better in reducing bacteria concentrations relative to OSW in sand and sandy loam soils, possibly because of the greater filtration properties related to soils with higher clay contents. There was nearly an order of magnitude difference in median coliform concentrations beneath OSW in sandy clay loam soils (6.59×10^3cfu/100mL) compared to sandy loam (2.16×10^4cfu/100 mL) and sand (2.21×10^4cfu/100 mL). There were approximately 10% and 21% increases in clay content between sand (3%) and sandy loam (13%) and sandy clay loam (24%) soils. The higher clay content (> 24%) seemed to greatly influence treatment efficiencies of OSW.

3.8 Groundwater Physical and Chemical Properties:

Significant differences were found comparing the electrical conductivity of the groundwater beneath OSW (higher) relative to background groundwater. Dissolved salts and solids increase the electrical conductivity of OSW effluent (Ptacek, 1998; Lee *et al.,* 2006). Thus electrical conductivity provided evidence of OSW influence on groundwater physical properties. Because groundwater pH beneath OSW was similar to septic tank effluent and elevated relative to background groundwater, this indicates that OSW were influencing groundwater chemistry.

4. 0 Conclusions:

Housing developments built on sandy, permeable, low iron content soils that use OSW could be significant sources of groundwater transported phosphorous and coliform. Many coastal environments are dominated by soils with characteristics that could allow significant PO_4 and coliform transport from OSW to ground and adjacent surface waters. Watersheds with more fine textured soils (> 24% clay) are less likely to have significant groundwater PO_4 and coliform contributions from OSW. Based on data from this and other studies, OSW nutrient and microbial contributions should be considered in watershed-scale management plans for watersheds with sandy soils and high densities of OSW. Watersheds with finer textured soils such as clay loams and clays are less likely to be significant sources of PO_4 and coliform.

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