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Evaluation of onsite sewage treatment and disposal systems in shallow karst terrain

Harmon S. Harden[a], *Eberhard Roeder*[b], *Mark Hooks*[b], *Jeffrey P. Chanton*[a,*]

[a]*Department of Oceanography, Florida State University Tallahassee, Tallahassee, FL 32306-4320, USA*

[b]*Florida Department of Health Bureau of Onsite Sewage Programs, Bin A08, 4052 Bald Cypress Way, Tallahassee, FL 32399-1317, USA*

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ABSTRACT

Two conventional onsite sewage treatment and disposal systems (OSTDSs) at Manatee Springs State Park, Florida, USA, were studied to assess their impact on groundwater quality in a shallow karst environment. Sulfur hexafluoride (SF_6) and fluorescein were used as tracers to establish connections between the drainfields and monitoring wells. Elevated nutrients were found in all wells where significant concentrations of both tracers were observed, with the mean of the highest nitrate (NO_3) concentration observed at each well being 47.8 ± 14.9 ($n = 11$) mg/L NO_3-N. The most elevated nutrient concentrations were found directly in the flow path of the effluent. Fecal coliform densities above 10 colony-forming units (cfu)/100 mL were observed in wells with the most rapid connection to the drainfield. The proximity and connectivity of the 0.4–4 m thick sandy surficial soils and the underlying karst aquifer allow rapid contaminant transport and limit the ability of conventional OSTDSs to attenuate NO_3.

1. Introduction

Onsite sewage treatment and disposal systems (OSTDSs) are an important part of Florida's wastewater infrastructure, serving about a quarter of the state's households and the 300,000 new arrivals per year (Social Science Data Analysis Network, undated; DOH, 2007). The proportion of homes served by OSTDS units is much higher in the rapidly growing, formerly rural areas of central and north Florida. In these areas, karst features, such as large springs, sinkholes, and caves, have formed in shallow limestone layers. These karst features have been shown to rapidly transport contaminants to and in the underlying groundwater (e.g. Price, 1988; Paul et al., 2000; Dillon et al., 1999, 2000).

Springs in most areas, except in national forests, have experienced degradation in water quality, particularly exhibiting elevated nitrogen concentrations (Florida Springs Task Force, 2006). While other sources such as fertilizer use, stormwater runoff, atmospheric deposition, and wastewater treatment plant discharge also contribute to water quality problems, the effects of conventional onsite sewage systems, consisting of a septic tank with a drainfield, have become of concern. The EPA has stated that "alternative systems may be necessary in karst areas" (EPA, 2006). In Florida, nutrient reduction is required for permanent onsite systems installed in the Florida Keys, where limestone is at the surface, lots are small, and allowable discharge methods include well injection (64E-6 Florida Administrative Code). In other karst areas of Florida, a larger drainfield is required when discontinuous limestone is encountered during site evaluation (DOH, 1999).

The objective of this study was to investigate the transport of septic tank effluent in shallow karst terrain covered by a sand layer, focusing on two goals. The first goal of this study was to examine the "connectivity" between the overlying

*Corresponding author. Tel.: +1 850 644 7493.
E-mail address: jchanton@fsu.edu (J.P. Chanton).

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sandy soil and the underlying karst aquifer. Two chemical tracers, SF_6 and fluorescein dye, were used to evaluate the subsurface flow pathways of the septic effluent and to unequivocally determine if the septic drainfield located above the karst and monitoring wells located within the karst aquifer are connected. The second goal of the study was to evaluate the conventional septic tank and drainfield method of OSTDSs in karst areas to determine if adequate removal of pathogen indicators and nutrients is being accomplished. Impacts of the septic drainfields on the surrounding groundwater quality were examined by comparing tracer and nutrient concentrations.

2. Methods

2.1. *Site selection and description*

The two study sites, Hickory and Magnolia, are located in wooded campgrounds within the Manatee Springs State Park on the lower Suwannee River (Fig. 1). Manatee Springs is a first-magnitude spring fed by an extensive cave system. Measured discharges have ranged between 3.1 and 6.7 m^3/s, and recent total NO_3 concentrations range between 1.7 and 2.0 mg/L NO_3-N (Scott et al., 2002; Florida Springs Task Force, 2006). The park had the advantages of being relatively isolated from outside sources of groundwater pollution, guaranteed access throughout the study, septic systems that were continuously in use, and the availability of local hydrologic data from the Suwannee River Water Management District.

The Lower Suwannee River Basin is part of Florida's karst area, where limestone, in this case Ocala limestone, has been dissolved to form solution channels (conduits), sinkholes, and springs. The lower Suwannee River is listed on Florida's impaired water list for elevated nutrient concentrations. Nitrogen and phosphorus are listed as co-limiting nutrients (DEP, 2002). Basin-wide, the contribution of OSTDS-derived NO_3 has been estimated to be less than 10% compared to other, largely agricultural, sources (Katz et al., 1999; DEP,

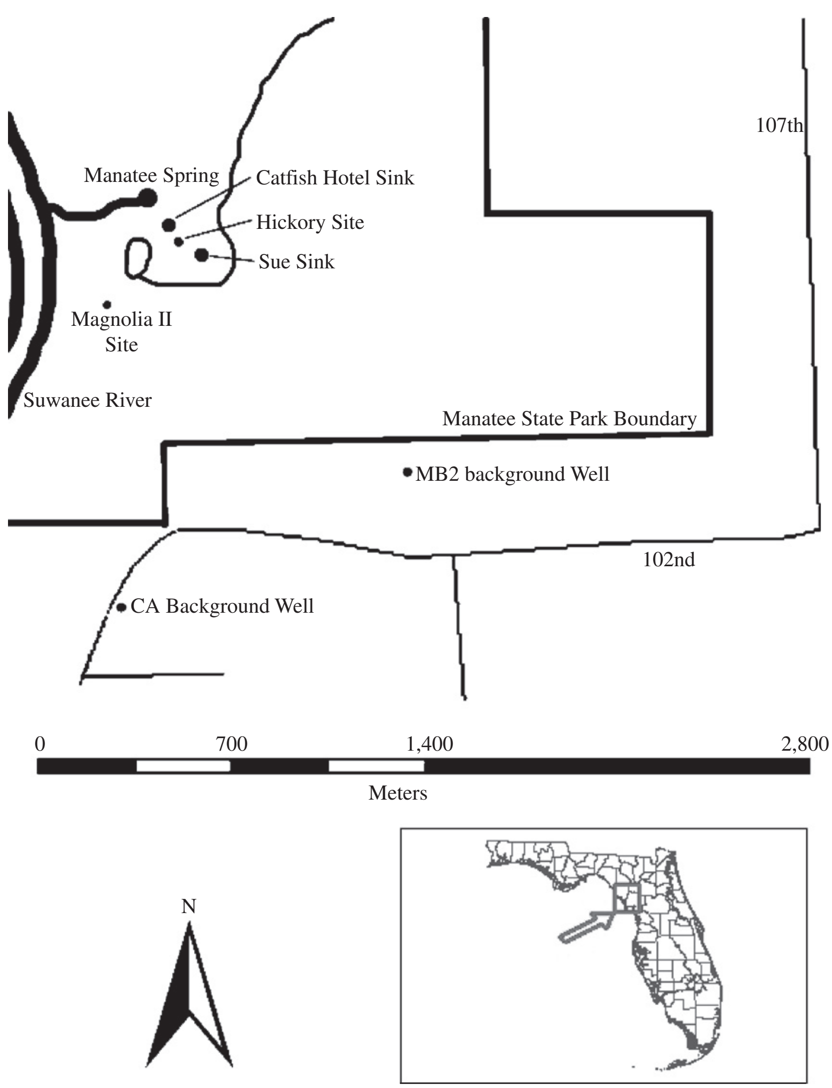

Fig. 1 – Map of study site. The two sites of study were the Magnolia II campground and the Hickory campground. The location of the site in the state of Florida, USA, is shown at the bottom of the figure.

2001). However, NO_3 loading from OSTDSs may be more significant in areas around springs where housing density is higher (DEP, 2001).

Two OSTDSs in slightly different hydrogeological settings were the focus of this study. The Magnolia site, located in the Magnolia II campground, is in close proximity to the Suwannee River and has a bathhouse and an OSTDS with a 1.5–2 m above-ground mounded drainfield for flood protection. Similar situations are frequently encountered in developments along the riverfront. The top of the drainfield mound is barely above the 10-year flood plain elevation of 4 m above the Suwannee River (SRWMD, undated). The water table was approximately 1–2 m below the ground surface, although this varied with fluctuations in the Suwannee River water levels. The Otela–Tavares soils surrounding the bathhouse area are associated with sandy karst uplands. These soils are moderately well drained white, gray, or light brown fine sands (Slabaugh et al., 1996).

The Hickory site, located in the Hickory campground, has a bathhouse with a conventional OSTDS (no mound) and a water table that is at least 3 m below the ground surface in non-flood conditions. The spring cave system is approximately 30 m below the ground surface and is directly beneath a portion of the drainfield, as documented by local cave diver depth gauges. The fine gray to light brown sands of the Jonesville–Otela–Seaboard complex in this area are associated with karst uplands and are well to moderately well drained (Slabaugh et al., 1996).

To characterize water quality unimpacted by OSTDS, two karst wells in undeveloped wooded areas on the park boundary were monitored for nutrient and fecal coliform concentrations.

2.2. *Ground-penetrating radar and locating wells*

The karst bedrock in the area is known to contain solution pipes, paleo-sinkholes, and other features that are not always visible by surface examination. These features are thought to rapidly connect the vertical movement of septic tank effluent through the soil. Ground-penetrating radar (GPR) has been successfully used in the region to identify these hidden features (Collins et al., 1990; Puckett et al., 1990). To locate depths to limestone and subsurface karst features (sinkholes and solution pipes), University of Florida soil scientists performed a GPR survey at Manatee Springs State Park in August 2001. Survey cross sections contained multiple signs of funnel-like structures in the limestone, which were interpreted as solution pipes and sinkholes. The GPR was used at the Hickory site to install well S1 within what was interpreted to be a paleo-sinkhole in the center of the drainfield and near a drainfield line. At Hickory, the presence of multiple surface water features and the geometry of the drainfield trenches complicated locating wells. Here, wells were installed to intercept travel of plumes from the drainfield trenches towards either of the two sinkholes. Wells were installed at Magnolia in a grid pattern to intercept the plume traveling from the OSTDS towards the river.

2.3. *Well installations*

Using a driller's rig, the Florida Geological Survey (FGS) installed 10 wells for groundwater quality and tracer sampling at each site (Figs. 2 and 3). Well installation was done without the use of driller's mud in order to minimize contamination of water quality samples. Wells were installed

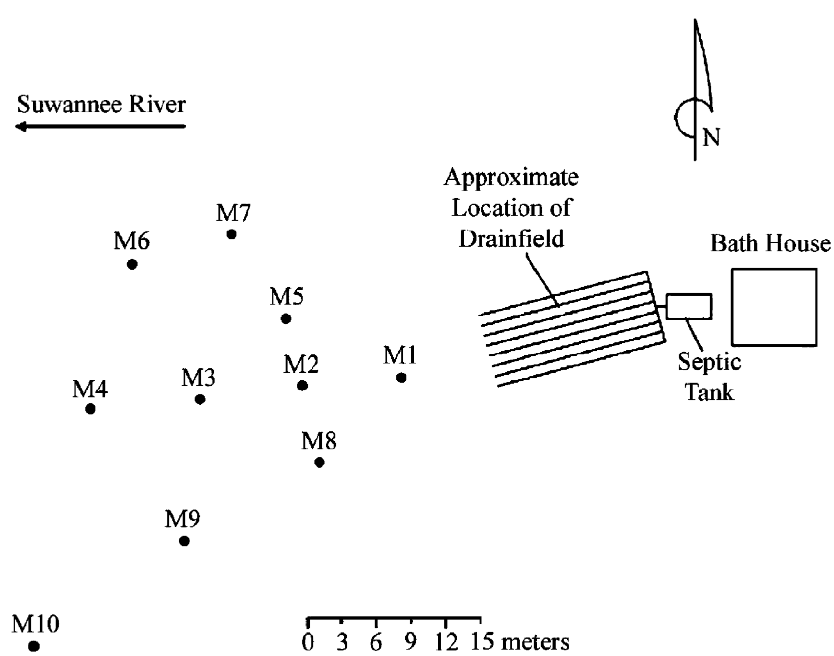

Fig. 2 – Magnolia site behind the Magnolia II campground bathhouse. Well M1 is in the lower portion of the drain mound slope. Wells M10, M4, and M6 are just in front of the cypress swamp adjacent to the Suwannee River. Groundwater flows towards the Suwannee River in a westerly direction. The order of fluorscene appearance in the wells was M8, M9, M5, M6, M3, M4, M7, M1, M2, M10.

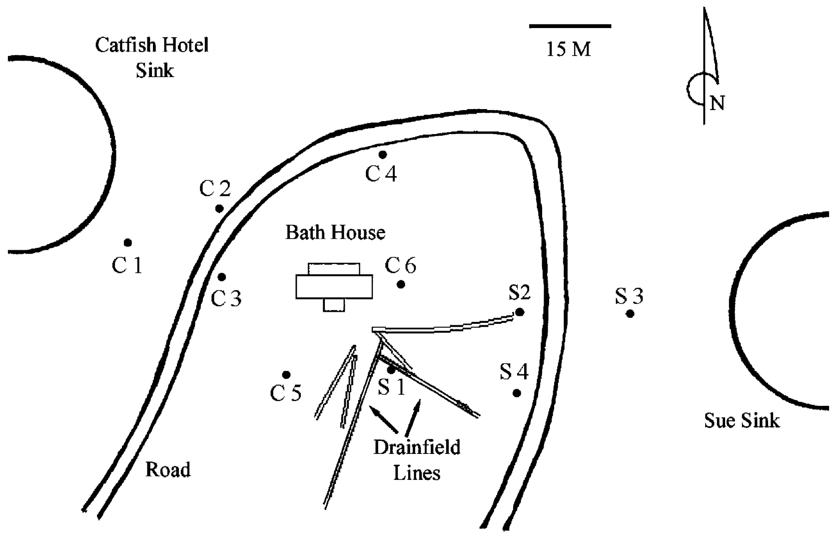

Fig. 3 – Study site at the Hickory campground. Well S1 is installed in a paleo-sinkhole as determined by the ground-penetrating radar study. Well S2 was installed at the end of a drainfield line. C1 was installed on the lip of the slope leading down to Catfish Hotel. Well S3 was installed on the lip of the slope leading to Sue Sink groundwater flows in a westerly direction and the main cave connects Sue Sink and Catfish Hotel Sink. Most observations of fluorscene were in wells S1, C5, and C6.

to a depth of at least 3 m below the water table at the time of installation. The wells were constructed with 3 m of 5 cm diameter PVC slotted well screen, silica sand filter pack, and Bentonite grout. The two background wells at the boundaries of the State Park, CA1 and MB2, were 10 cm diameter wells installed in cooperation with the Suwannee River Water Management District and FGS.

Water levels in the wells at the time of installation were between 1.3 and 2.5 m below the surface at Magnolia, and at Hickory they were 4–4.5 m below the surface. For the background well CA1 the water table was 2.8 m from the surface and for well MB2, 4.6 m at the time of installation. The depth to limestone, depth to top of screen, and total depth of each well are given in Table 1.

2.4. Tracer injections

The injection solution was added by gravity feed into the pipe that connects the septic tank with the distribution box and drainfield. This avoided dilution of the injection slug and binding of the fluorescein to organic matter in the septic tank. Prior to each injection, background samples were collected from the well field. The Magnolia site was injected on May 24, 2003 with a solution consisting of approximately 500 g of fluorescein dye dissolved into approximately 160 L of tap water which was bubbled with 99.8% pure SF_6 (Scott Specialty Gases) for at least 45 min. The injection slug was added to the drainfield over a 45-min period by gravity feed while the solution was gently bubbled with SF_6 to counteract any SF_6 degassing. An additional 20 L of tap water was used to rinse the container and flush the injection solution from the distribution pipes into the drainfield. This was repeated at the Hickory site on July 4, 2003, except that the injection time was decreased to 20 min. At both sites the water table was approximately 3 m below the injection point. The SF_6 concentration from three samples of the injection slug taken during the injection period was 41.8 ± 1.3 μM ($n = 3$) at the Magnolia site and 37.9 ± 8.0 μM ($n = 3$) at the Hickory

Table 1 – Well information for the background wells (CA and MB2) and wells at Hickory (C# and S#) and Magnolia (M#)

Well ID	Depth to limestone (m)	Depth to screen (m)	Total depth (m)
Backgound wells			
CA1	7.35	2.32	8.53
MB2	0.0	2.74	8.84
Magnolia site			
M1	1.83	4.94	9.45
M2	1.37	2.13	7.62
M3	2.44	3.05	9.14
M4	4.57	5.88	10.67
M5	2.29	5.12	9.75
M6	1.92	3.51	8.23
M7	0.37	4.42	8.84
M8	0.61	4.02	8.84
M9	0.76	3.60	22.86
M10	0.76	2.96	7.62
Hickory site			
C1	0.40	3.66	10.36
C2	0.73	4.11	10.67
C3A	2.83	4.33	10.67
C4	4.42	4.72	10.36
C5	1.19	4.48	10.67
C6	0.94	4.57	10.67
S1	1.01	4.72	10.67
S2	0.55	4.42	10.36
S3	2.44	3.81	10.36
S4	0.43	4.57	11.89

The depths are from the ground surface and are given in meters.

site. The fluorescein concentration in the injection slug was 3242±73 mg/L ($n = 3$) at the Magnolia site and 2851±26 mg/L ($n = 3$) at the Hickory site. The midway point of the injection process was used as the starting time in travel velocity calculations.

2.5. Sample collection

All samples were collected using a submersible purge pump. At least three well volumes were pumped prior to any sampling. Approximately a third of the purge water was pumped from the top of the water column, then the next third from the middle of the water column, and the final third from the bottom of the well. Well C5 was the only well that pumped dry during purging, all the other wells recharged quickly. The same sample tubing was used for all the wells, and high volumes of purge water (>55 L) were thought to sufficiently rinse the tubing before sampling. The purge water was collected in buckets and dumped downstream of the well field at the Magnolia site. At the Hickory site, the purge water was dumped into an outside sink connected to the septic system and located behind the bathhouse. Prior to sampling the pump was moved back within approximately a meter of the top of the water column. Samples for nutrients and fecal coliforms were collected from the wells in containers provided by the analytical laboratory. Sulfur hexafluoride (SF_6) samples were collected in 30-mL serum vials. The vial was allowed to overflow for at least three bottle volumes, and was then sealed with a rubber septum and a crimp cap. Fluorescein samples were collected and stored in 100-mL amber polycarbonate containers.

A total of nine sampling events for water quality occurred between February 19, 2003 and May 10, 2004, although not all wells were sampled during every sampling event. Due to high water conditions on April 1, 2003 at Magnolia only wells M1 and M2 were sampled as the rest were submerged. The Hickory campground was closed for renovation on September 4, 2003, 62 days after the tracer injection. After the September 19, 2003 sampling date, only wells S1, C5, and C6 were sampled. C6 was last sampled on December 3, 2003, 152 days after injection. Between the December 3, 2003 and January 26, 2004 sample dates, well C6 was damaged by construction activity, preventing further sampling. The Hickory campground reopened on May 3, 2004. The two background wells CA1 and MB2 were sampled 5 times between February 19, 2003 and August 22, 2003.

2.6. Nutrient and fecal coliform analysis

Samples were transported on ice to the laboratory and analyzed for fecal coliforms (SM9222D), total phosphorus (TP) (EPA 365.3), total ammonia (EPA 350.2), total Kjeldahl nitrogen (TKN) (EPA 351.3), nitrite-nitrogen (SM 4500NO2B), and NO_3-N (EPA 353.3). The predominant nitrogen species was NO_3 in all samples that had a total nitrogen concentration of more than 2 mg/L NO_3-N, and therefore the discussion of results will focus on NO_3. For all NO_3 and TP average calculations, any samples below the detection limit of 0.012 mg/L NO_3-N for NO_3 and of 0.014 mg/L for TP were considered zero (Tables 2 and 3).

2.7. SF_6 sample analysis

SF_6 samples were extracted as described by Dillon et al. (1999) and Harden et al. (2003). A small headspace of 4 mL of ultra-high-purity nitrogen was added to the samples using a syringe. Simultaneously, 3 mL of water from the sample was removed and discarded to allow room for the headspace. The serum vials were slightly over-pressurized with 1 mL of nitrogen to allow for several injection volumes (100 μL or less) for the gas chromatograph (GC). After shaking for at least 2 min, this method extracts 95+% of the SF_6 from a water sample. The lower limit of this technique is 0.1 pM (Dillon et al., 2000). Samples were analyzed with a Shimadzu

Table 2 – For the background wells (CA1 and MB2) and each well at the Magnolia site, both the average and highest concentrations for NO_3 and TP are presented along with the highest tracer concentrations

Well ID	High TP (mg/L)	Average TP (mg/L)	High NO_3 (mg/L NO_3-N)	Average NO_3 (mg/L NO_3-N)	High SF_6 (pM)	High Fl (mg/L)
CA1	0.03	0.01±0.01	0.15	0.07±0.06		
MB2	0.47	0.18±0.17	1.61	0.61±0.74		
M1	0.45	0.35±0.12	49.8±18.8	29.4±9.8	12.5	1.5
M2	0.80	0.76±0.28	63.2	22.8±17.5	16.1	2.8
M3	0.73	0.54±0.12	33.9	14.9±11.2	8.2	1.9
M4	0.19	0.12±0.27	0.77	0.25±0.23	0.75	0.06
M5	1.14	0.24±0.39	62.6	26.1±15.2	8.7	1.3
M6	0.92	0.13±0.32	51.4	17.5±14.5	4.1	0.36
M7	1.24	0.34±0.40	63.3	19.4±17.7	3.9	0.51
M8	1.32±0.06	0.93±0.24	54.6±14.7	30.1±17.1	17.0	11.0
M9	0.15	0.03±0.06	35.9	6.9±12.6	4.3	5.6
M10	0.05	0.01±0.02	0.15	0.03±0.05	0.27	0.01

For the nutrient samples from the background wells $n = 5$, wells M1 and M2 $n = 9$, and the remaining eight wells $n = 8$.

Table 3 – For the background wells (CA1 and MB2) and each well at the Hickory site, both the average and highest concentrations for NO_3 and TP are presented along with the highest tracer concentrations

Well ID	High TP (mg/L)	Average TP (mg/L)	High NO_3 (mg/L NO_3-N)	Average NO_3 (mg/L NO_3-N)	High SF_6 (pM)	High Fl (mg/L)
CA1	0.03	0.01±0.01	0.15	0.07±0.06		
MB2	0.47	0.18±0.17	1.61	0.61±0.74		
S1	4.89	1.1±1.4	56.1	21.9±16.1	12.7	1.3
S2	0.04	0.012±0.017	1.1	0.58±0.38	0.25	0.009
S3	0.70	0.21±0.28	0.08	0.05±0.03	0.19	0.02
S4	0.26	0.08±0.11	0.49	0.28±0.19	0.18	0.008
C1	0.03	0.005±0.013	0.72±0.18	0.39±0.24	0.22	0.005
C2	<0.014	<0.014	1.6	0.48±0.18	0.21	0.002
C3	0.05	0.014±0.021	1.1	0.59±0.30	0.26	0.002
C4	0.03	0.014±0.013	1.23	0.71±0.33	0.25	0.01
C5	0.17	0.05±0.08	41.3	11.7±14.7	1.1	0.07
C6	0.03	0.005±0.012	22.9	5.0±8.0	1.2	0.11

For the nutrient samples, background wells and wells C1, C2, C3, C4, S3, and S4 $n = 5$, wells C6 $n = 6$, and wells S1 and C5 $n = 9$.

model 8A GC equipped with an electron capture detector as described in Harden et al. (2003). Headspace concentrations in ppmv (parts per million by volume = μL/L) of SF_6 were determined by reference to a 1.04 ppmv standard (Scott Specialty Gases). Headspace concentrations were converted to dissolved concentrations in pM.

2.8. *Fluorescein dye analysis*

The fluorescein samples were analyzed using a Turner Designs TD-700 Fluorometer, which provides exact concentrations after calibration. The fluorometer used a 10-089 blue mercury vapor lamp, 10-105 excitation filter (486 nm), and 10-109R-C emission filter (510–700 nm), as specified by the manufacturer. The fluorometer was initially calibrated using fluorescein standards made using DI water in the laboratory with a lower detection limit of 0.0005 mg/L. Calibration was checked several times daily by use of solid-state standards.

2.9. *Statistical analysis*

Statistical significance of differences was assessed using a non-parametric multiple comparison procedure based on the Kruskal–Wallis test (Cabilio and Masaro, 2001). This procedure compares observed differences in the mean ranks of groups of analytical results to expected random variations and is insensitive to the numerical value assigned to samples with concentrations below detection limits. Wells were grouped into four groups based on the tracer test results: (1) background wells, (2) wells with relatively low tracer concentrations, (3) wells with intermediate tracer concentrations, and (4) wells with high tracer concentrations. Group membership was uniquely determined by requiring consistency between the two tracers and coincided in seven out of eight cases with natural breaks in the observed concentration levels.

3. Results

3.1. *Tracer experiment at Magnolia*

Approximately 6 h after injection, the tracer solution was observed pooling on the ground approximately 1.5 m in front of well M8. Apparently, a portion of the injection slug flowed laterally towards well M8. Within an hour, a sizable puddle had grown to approximately 1 × 2 m, with the edge just over a meter in front of M8. This puddle doubled in size over the next day before starting to subside.

The first fluorescein peak was observed a day after injection on the south side of the well field in well M8, which had the highest concentration measured during the experiment (Fig. 4, Tables 2 and 4). Well M9, closer to the river (Fig. 2), was the second well to exhibit a peak with the second largest fluorescein concentration (Tables 2 and 4). On the second and third days, fluorescein peaks were observed on the north side of the well field in well M5 and then M6. On the fourth day of the experiment, a fluorescein peak was observed in the center of the well field in M3. Although center wells M1 and M2 are closer to the drainfield than M3 (Fig. 2), peaks were not observed in these wells until days 18 and 23, respectively. Fluorescein concentrations were 1–2 orders of magnitude lower in wells M4 and M10 than in the other wells (Table 2). Only in well M10 was there a single observation of fluorescein; all other wells had multiple observations. The concentration of fluorescein observed in the wells was diluted by a factor of 1000 relative to the injection slug.

The SF_6 tracer behaved differently from the fluorescein. The SF_6 took much longer to rise to peak concentrations and stayed elevated longer than did the fluorescein (Table 4, Figs. 4 and 5). Well M2 was the first well to have an observed SF_6 peak at 37 days after injection. On day 69, peak SF_6 concentrations were observed at both wells M1 and M8 (Fig. 4). Well M3 had an SF_6 peak on day 118 and at the remaining wells the peak SF_6 concentration was

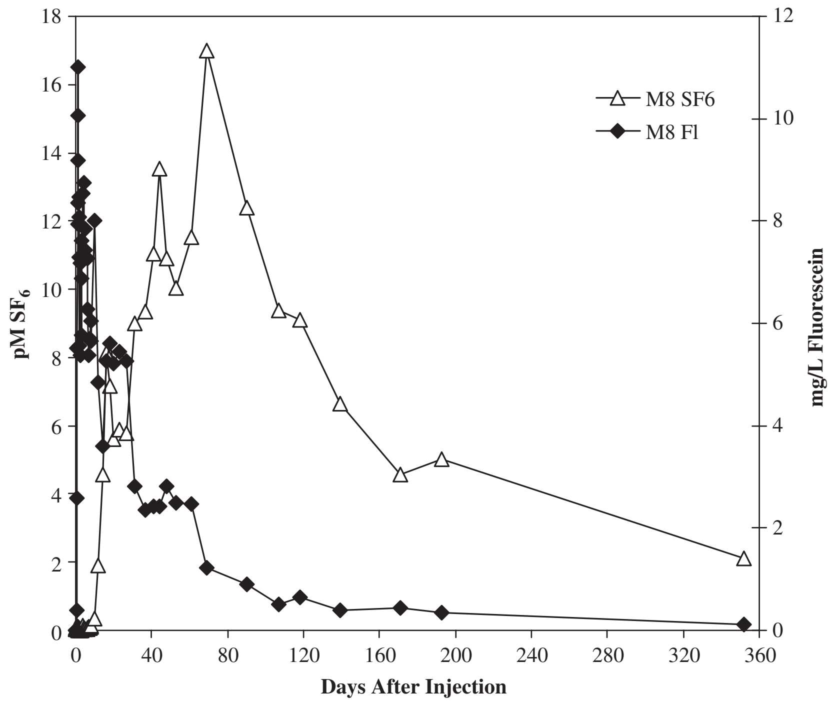

Fig. 4 – Sulfur hexafluoride (open symbols) and fluorescein (closed symbols) data for well M8 during the Magnolia tracer study. The drainfield was injected on May 24, 2003. The highest fluorescein and sulfur hexafluoride concentrations observed in any well during the experiment occurred in well M8. The highest fluorescein concentration of 11.0 mg/L was observed 1.13 days after injection. The highest sulfur hexafluoride concentration, 17.0 pM, was observed 69.2 days after injection. The average nitrate concentration at this well was the highest observed in the experiment.

Table 4 – For each of the Magnolia monitoring wells and the three Hickory wells where the tracers were observed, the well ID, distance (m) from injection point, and number of days following injection that the peak SF_6 and fluorescein concentrations were observed

Well ID	Distance (m)	Fl peak (days)	SF_6 peak (days)	Velocity F (m/day)l	Velocity SF_6 (m/day)	Tracer level
M1	22.9	18.1	69.2	1.3	0.3	High
M2	32.2	22.9	37.0	1.4	0.9	High
M3	41.1	4.1	118	10.0	0.3	High
M4	50.3	8.3	171	6.1	0.3	Low
M5	32.5	2.2	171	14.8	0.2	High
M6	46.2	3.2	171	14.4	0.3	Intermediate
M7	38.0	10.0	171	3.8	0.2	Intermediate
M8	32.8	1.1	69.2	29.8	0.5	High
M9	46.2	1.8	171	25.7	0.3	High
M10	62.4	171	171	0.4	0.4	Low
S1	10.5	2.8	27.9	3.8	0.4	High
C5	14.2	39.9	77.0	0.4	0.2	Intermediate
C6	12.4	98.0	66.0	0.1	0.2	Intermediate

measured on day 171 (Tables 2 and 4). The SF_6 concentration observed was diluted by a factor of 10^6 relative to the injection slug.

Wells M4 and M10 had low peak tracer concentrations (0.51 ± 0.34 pM SF_6, 0.04 ± 0.4 mg/L fluorescein) and formed the low peak tracer group (see Section 2.9); M6 and M7 with the next lowest tracer concentrations (4.0 ± 0.14 pM SF_6, 0.44 ± 0.11 mg/L fluorescein) were assigned to the intermediate peak tracer group. The six other wells formed the high peak tracer group (11.3 ± 4.94 pM SF_6, 4.02 ± 3.77 mg/L fluorescein).

3.2. *Magnolia water quality*

NO_3 concentrations exceeded the drinking water standard of 10 mg/L NO_3-N in many instances at this site. NO_3 concentrations were consistently above background concentrations in all wells except M4 and M10. The mean of the highest NO_3

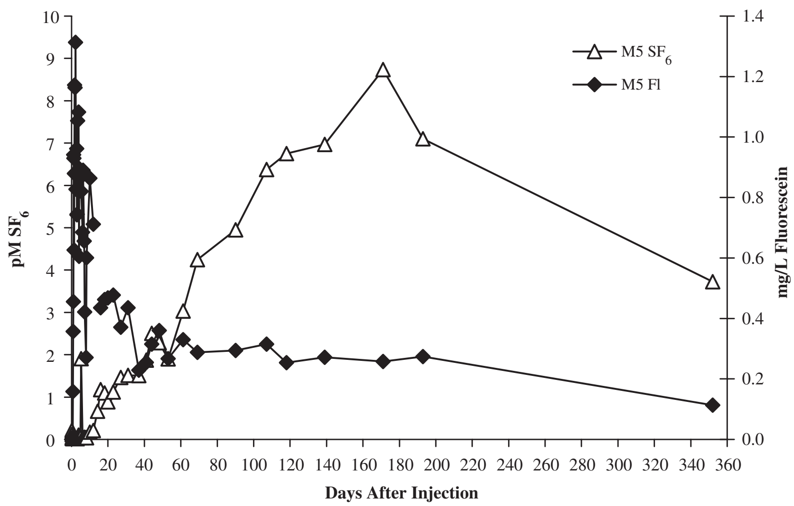

Fig. 5 – Sulfur hexafluoride (open symbols) and fluorescein (closed symbols) data for well M5 during the Magnolia tracer study. The drainfield was injected on May 24, 2003. The highest concentrations observed in this well were 1.31 mg/L fluorescein at 2.19 days and 8.74 pM sulfur hexafluoride at 171 days after injection.

concentration observed in these wells was 47.8 ± 14.9 ($n = 8$) mg/L NO_3-N (Table 2). NO_3 concentrations were significantly higher in wells where intermediate and high tracer concentrations were observed relative to background wells and low tracer concentration wells (M4 and M10). NO_3 concentrations at M4 and M10 were not significantly elevated concentrations relative to the background wells (Table 2). Of eight sampling events, well M10 had four samples below the detection limit of NO_3. NO_3-N in well M9 was near background until the last two sampling events when it rose to 13.8 mg/L NO_3-N on January 26, 2004 and 35.9 mg/L NO_3-N on May 10, 2004. Differences between wells M6 and M7, with intermediate tracer concentrations, and the wells with high tracer concentrations were not significant for NO_3-N. TP was significantly elevated in the wells with high tracer concentrations relative to background and wells with low (M4, M10) and intermediate (M6, M7) peak tracer concentrations (Table 2 and 4). The highest concentrations of TP at the Magnolia site were found in M8, followed by M2 and M3 (Table 2).

Fecal coliforms were not consistently present in any of the wells, but were found sporadically in several wells. In the two background wells, fecal coliforms were not ever above the detection limit of 2 cfu/100 mL. The highest number of fecal coliforms, 932 cfu/100 mL, was found in well M8. The only other wells to have more than 100 cfu/100 mL were M5, 159 cfu/100 mL, and M6, 114 cfu/100 mL. There were no significant differences between peak tracer groups because only few samples in the intermediate and high tracer groups showed high fecal counts. The complete fecal coliform and nutrient data are found in DOH (2004).

3.3. *Tracer experiment at Hickory*

Fluorescein was observed multiple times in wells S1, C5, and C6. Well S1 had the highest concentrations of fluorescein observed in the Hickory campground experiment, with a concentration peak measured at 3 days (Fig. 6). Well C5 had the next highest concentration peak of fluorescein, measured on day 40. On day 98, a peak was observed in well C6. In wells S3 and C4, fluorescein was observed once at low concentrations at 1.2 days (Tables 3 and 4). The remaining wells did not have fluorescein observations above 0.01 mg/L. Fluorescein concentrations less than 0.005 mg/L were considered background readings. Small concentrations of fluorescein were observed in Catfish Hotel, 0.017 mg/L, and the spring, 0.008 mg/L, both at 20.1 days after injection. Fluorescein was not observed either in Sue Sink or inside the cave system. However, it should be noted that the cave was only sampled on 1 day and Sue Sink was only sampled for the first 5 days of the experiment.

As with fluorescein, the highest SF_6 concentrations were observed in wells S1, C5, and C6 (Fig. 6). The largest peak was observed in well S1 on day 28, and smaller peaks were observed in C6 on day 66 and C5 on day 77 (Tables 3 and 4). In the remaining seven wells, smaller peak concentrations were observed (<0.3 pM) within the first 3 days. Since these observations were relatively small and occurred early in the experiment, they may be a result of SF_6 traveling through the air in the vadose zone or even at ground level and were considered an artifact from the injection.

At this site, well S1 formed the high peak tracer group (12.7 pM SF_6, 1.3 mg/L fluorescein), wells C5 and C6 (1.15 ± 0.07 pM SF_6, 0.09 ± 00.03 mg/L fluorescein) formed the intermediate tracer group, and the remaining seven wells formed the low peak tracer group. As at the Magnolia site, the well SF_6 concentrations were diluted by a factor of 1000-fold more that was fluorescein relative to the injection slug.

3.4. *Hickory water quality*

NO_3 concentrations in excess of the drinking water standard of 10 mg/L NO_3-N were found in the wells with high (S1) and intermediate tracer concentrations (C5 and C6). These three

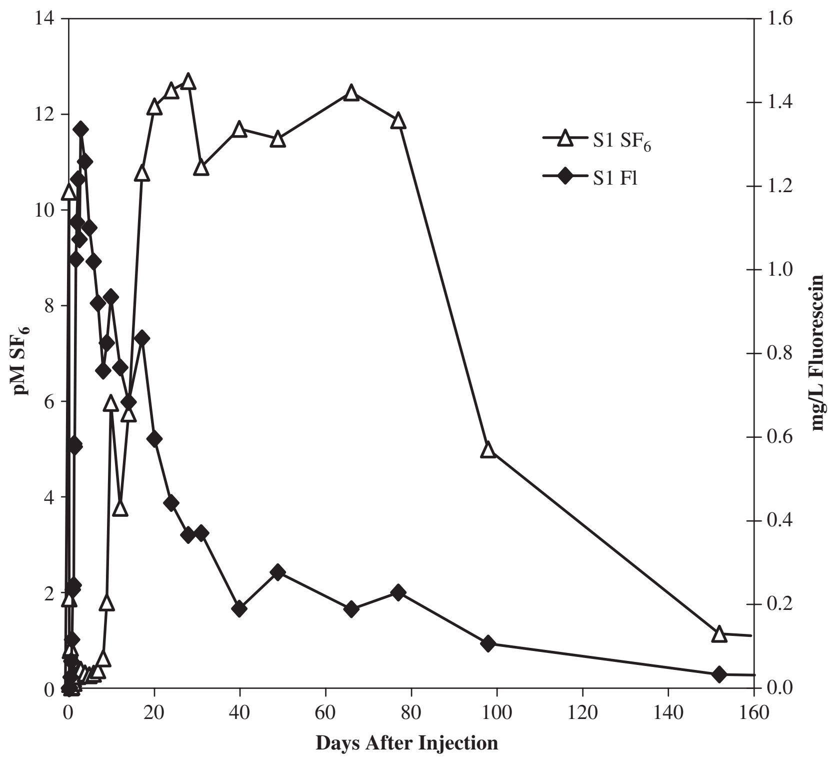

Fig. 6 – Sulfur hexafluoride (open symbols) and fluorescein (closed symbols) data for well S1 during the Hickory tracer study. The drainfield was injected on July 4, 2003. The highest concentrations observed in this well were 1.34 mg/L fluorescein at 2.80 days and 12.7 pM sulfur hexafluoride at 27.9 days after injection. Well S1 is located within a paleo-sink. Samples were taken at 311 days and 0.26 pM sulfur hexafluoride was observed and fluorescein was 0.06 mg/L, near the background fluorescence of 0.005 mg/L.

wells had significantly elevated concentrations of NO_3 and a lower fraction of TKN compared to the background wells and the wells with low peak tracer concentrations (Table 3). Well S1, with highest concentration of both tracers, had the highest NO_3 concentrations ranging from 4.28 ± 0.02 to 56.1 mg/L NO_3-N. Well C5 had the next highest average NO_3 concentrations with a range of 1.8–41.3 mg/L NO_3-N. For the first five sampling events for well C6, the NO_3 concentrations averaged 1.43 ± 0.33 ($n = 5$) mg/L NO_3-N; however, elevated NO_3 concentrations of 22.9 and 5.21 mg/L NO_3-N were measured on the last two sampling events. The differences in mean ranks of NO_3-N concentrations between S1 on the one hand and C5 and C6 on the other were not significant.

The TP concentrations in the Hickory well field were generally very low. Well S1, with high peak tracer concentrations, showed significantly higher TP concentrations than background wells, low, and intermediate peak tracer wells. In every sample from well S1, the TP was higher than background wells with a range of 4.89–0.41 mg/L. Intermediate and low peak tracer wells were not significantly different from each other and from background.

Fecal coliforms were found sporadically in a few wells, notably in those wells where elevated TP was observed. Counts of 99 cfu/100 mL and 40 cfu/100 mL were observed in well S1, and counts of 74 cfu/100 mL and 124 cfu/100 mL were observed in well S3. Other wells had concentrations of less than 10 cfu/100 mL in all samples. The complete nutrient and fecal coliform data can be found in DOH (2004).

3.5. *Comparison of the subsurface tracer flow rates*

Peak arrival time was used to calculate the velocity of the tracers in this study. Tracers were injected just upstream of the drainfield. The residence time of the effluent in the drainfield increases the span of time between the injection and when the tracer slug actually enters the water table. The fluorescein and SF_6 tracers showed two distinct patterns. An early, sharp peak with a long tail characterizes the fluorescein tracer data, while the SF_6 concentrations took many days to weeks to rise to peak concentrations and also exhibited a long tail (Figs. 4–6). The wide peak in the SF_6 data suggests that using a half-peak value may be more appropriate. However, in order to calculate travel velocities from the two data sets by the same method, the arrival time of the tracers was estimated to be when the peak concentration was observed. Using the peak concentration yields a more conservative estimate of the travel velocities and allows for direct comparison with other studies.

At Magnolia the SF_6 velocity was calculated to be 0.4 ± 0.2 m/day ($n = 8$) (Table 4). Both wells M4 and M10 had much lower concentrations of nutrients and tracers than the other wells (Table 2), indicating that these wells were not sampling the main effluent plume; therefore velocities from these wells were not included. The travel velocity for the fluorescein was calculated to be 12.6 ± 10.8 m/day ($n = 8$) (Table 4).

At Hickory, tracer velocities were calculated for wells S1, C5, and C6. The tracer and nutrient data indicate that the remaining wells were not sampling the effluent plume (Table 3). The Hickory SF_6 velocity of 0.2 ± 0.1 m/day ($n = 3$) was similar to the results of the Magnolia study. The fluorescein velocity at Hickory was 1.4 ± 2.0 m/day ($n = 3$). The average tracer velocities from both experiments were 0.3 ± 0.2 m/day ($n = 11$) for SF_6 and 9.6 ± 10.5 m/day ($n = 11$) for fluorescein. The fluorescein velocity at well S1 (3.8 m/day) was in the same range as the Magnolia fluorescein results.

4. Discussion

4.1. *Tracer experiments*

The results of the tracer experiments at the Magnolia and Hickory campgrounds illustrate the complexity of the subsurface flow in a karst environment. Groundwater can flow through conduits in the karst (conduit flow) or flow through the matrix of the rock or unconsolidated sediments (matrix flow). Flow was observed to bypass a well in close proximity to the drainfield, and then appear at a well further downfield. Tracers can and also arrive at a single well multiple times via multiple pathways (Field, 2002). Multiple peaks were observed at several wells (e.g. Figs. 4–6).

The two tracers employed have very different characteristics; one is an inert conservative gas, the other a non-conservative fluorescent dye. Fluorescein is known to bind to carbonate and organic material (Kasnavia et al., 1998; Omoti and Wild, 1979) and therefore its flow may be retarded (Harden et al., 2003). Exchange of the tracer between the conduits and the matrix could have been a factor in the observed tailings in the fluorescein breakthrough curves. SF_6 will degas from systems exposed to an atmosphere, which could have occurred during flow though a partially filled conduit or as the injection slug flowed through the drainfield, the vadose zone, or across the soil surface. The 1000-fold greater dilution of SF_6 in wells relative to fluorescein compared to the injection slugs indicates that significant degassing did occur at both sites. The tracers were added upstream of both drainfields, which were some 3 m above the water table at both locations. Due to the limitations of both tracers, the tracer travel velocities may not be representative of the actual groundwater velocity, but are very useful in demonstrating the connectivity of the septic systems and the wells. Relative rates of tracer flow are of interest in comparison to other studies (e.g. Dillon et al., 1999, 2000, 2003; Corbett et al., 2000; Harden et al., 2003).

In addition to experiencing greater dilution relative to fluorescein, in the well samples relative to the injection slug, SF_6 flow rates were significantly retarded relative to fluorescein. It is possible that the two tracers followed different paths to the wells due to degassing of the SF_6 along the fluorescein path. Olsen and Tenbus (2004) also observed different rates of flow between fluorescein and SF_6 and postulated that the difference could have arisen due to gas-bubble rise and trapping.

Observations at well M8, where the tracer-laden puddle appeared early in the Magnolia experiment, illustrate this difference in each tracer's behavior. Due to degassing, the puddle acted as a second injection point for fluorescein, but not for SF_6. The correlation between peak SF_6 concentration and peak fluorescein concentration increases from $r^2 = 0.39$ ($n = 10$, $p = 0.055$) to $r^2 = 0.89$ ($n = 8$, $p = 0.0005$) when the wells near the puddle (M8 and M9) are excluded. This indicates that SF_6 was removed when the puddle seeped back into the ground, as these two wells were directly downstream of the puddle. The high concentration of fluorescein of the injection slug could have caused a density effect, where the injection slug would sink before dilution into the groundwater. The observation of the injection slug on the surface suggests this may not have been an over-riding factor in this experiment.

While a general pattern of slower tracer velocities nearer to the drainfield could suggest slower transport in the drainfield and vadose zone relative to the velocity in downstream groundwater flow, such a pattern is absent. Instead, fluorescein peaks appear in wells such as M8, M9, and M5 before the first peak even appears at the closest well, M1, suggesting that different conduits are intercepted by different wells (Figs. 4 and 5).

The fluorescein results indicated that this tracer did not travel fastest straight west from the drainfield mound towards the river. Instead, the fastest flow was towards the south side of the well field. Among wells with high and intermediate tracer concentrations, the south-side wells M8 and M9 had higher fluorescein velocities, 29.8 and 25.7 m/day respectively, than did the north-side wells M5 (14.8 m/day), M6 (14.4 m/day), and M7 (3.8 m/day). In the center of the well field, the fluorescein velocities close to the drainfield mound in wells M1 (1.3 m/day) and M2 (1.4 m/day) were less than those away from the mound in well M3 (10.0 m/day (Table 4)). The fluorescein that flowed to M3 apparently followed another pathway than the effluent flowing towards M1 and M2. Without M1 and M2, the average travel velocity for the rest of the wells in the effluent plume is 16.4 ± 9.7 m/day ($n = 6$). The SF_6 data from Magnolia yielded more uniform travel velocities throughout the well field than the fluorescein data, with an average of 0.4 ± 0.2 m/day ($n = 10$), including the low tracer level wells M4 and M10.

At the Hickory site, the wells with the highest SF_6 concentrations, S1, C5 and C6, also contained the highest fluorescein concentrations. There was a strong correlation between the SF_6 and fluorescein peak concentrations ($r^2 = 0.99$, $n = 10$, $p < 0.0001$). The tracer data for well S1 exhibited a similar pattern to the wells at Magnolia; an early sharp fluorescein peak, followed by a wide SF_6 peak, both with long tails (Figs. 4–6). The travel velocity of 3.8 m/day calculated from the S1 fluorescein data is within the range of velocities calculated from the fluorescein data in the Magnolia wells, 12.6 ± 10.8 m/day ($n = 8$). The S1 SF_6 travel velocity of 0.4 m/day is similar to the SF_6 velocities from Magnolia, 0.4 ± 0.2 m/day ($n = 8$). The fluorescein travel velocities for wells C5 (0.4 m/day) and C6 (0.1 m/day) (Table 4) indicate that there were no direct conduit connections between the drainfield and the wells. The SF_6 travel velocities are consistent between S1 and the Magnolia wells.

4.2. Nutrient and tracer data comparisons

At both sites, tracer data correspond with nutrient data, confirming that most of the nutrients found in the well fields are in fact from the septic systems. The wells with the highest tracer concentrations had the highest NO_3 and TP concentrations (Tables 2 and 3). Those wells with the lowest tracer concentrations (M4 and M10 at Magnolia and C1 through C4, S2, and S3 at Hickory) did not differ significantly in nutrient concentrations from background wells. Concentration changes in well S1 in response to changes in activity at the Hickory bathhouse changes appear to confirm the septic system as source. Following closure of this campground on September 3, 2003, the NO_3-N concentration in S1 decreased from an average to 27.4 mg/L NO_3-N and a high of 56.1 mg/L NO_3-N on August 22, 2003 to 7.77 mg/L on October 10, 2003 and 4.28 ± 0.02 mg/L NO_3-N on January 26, 2004. The campground was reopened on May 3, 2004, and just 1 week later the NO_3 concentrations increased again in well S1 to 35.95 ± 3.32 mg/L NO_3-N. The rapid response is consistent with the fluorescein tracer travel times for S1.

4.3. Fluorescein in the spring and sinks

Fluorescein was found in the spring, Sue Sink, and Catfish Hotel during the Hickory experiment. On day 20, 0.017 mg/L of fluorescein was observed at Catfish Hotel and 0.008 mg/L in the spring. The previous 16 samples at both Catfish Hotel and the spring had a background fluorescence of $\leqslant 0.002$ and $\leqslant 0.001$ mg/L fluorescein, respectively. These results suggest connectivity between the drainfield and the spring and sinks.

4.4. Nutrient attenuation

The concentration of NO_3-N exceeded the drinking water standard in many wells and reached concentrations similar to literature values for dissolved NH_4^+-N, the main form of N in septic tank effluent (e.g. McCray et al., 2005). Unfortunately, septic tank effluent concentrations were not measured in this study. The high fraction of NO_3 in total nitrogen measurements (DOH, 2004) suggests that the vadose zone was sufficiently oxygenated to allow nitrification. To assess roughly the extent of denitrification, an approach using a first-order reaction rate with respect to the fraction of organic carbon (FOC) suggested by Anderson (1998) is applied using the following equation:

Loss of NO_3 (mg/L/day) = bulk density × (0.442 × (FOC in %)+0.0194).

Assuming an FOC of 0.5% as the upper boundary of soil horizons below the drainfield (Slabaugh et al., 1996), and the highest peak tracer travel time of about 20 days observed at M1 and M2, about 8 mg/L NO_3-N could potentially be removed by denitrification, less than 20% of the observed maximum concentration and about a third of the average concentration. At a travel time of 5 days, only about 2 mg/L NO_3-N could be removed, which would not have been discernable in the observations. The extensive tailing of tracers suggests that the average travel time for nitrogen could have been higher than the peak arrival time, and denitrification could have been somewhat greater.

In contrast to the nitrogen observations, the maximum observed TP concentrations, 4.9 mg/L at Hickory and 1.2 mg/L at Magnolia, are much lower than typically observed in septic tank effluent (McCray et al., 2005). This suggests that phosphorus is fixed, by sorption or precipitation, in the vadose zone or in the limestone rock, as observed by Dillon et al. (2003). This is in agreement with observations by others as reviewed by McCray et al. (2005). The significant difference in TP concentrations between wells with intermediate and high peak tracer concentrations suggests that relative to nitrogen, more attenuation of TP takes place in the subsurface.

4.5. Fecal coliform attenuation

The results of this study indicate that in the karst environment, conventional septic systems remain relatively efficient in removing fecal coliforms. The few high fecal counts did not result in significantly higher rank order statistics for the impacted wells relative to background or unimpacted wells. Except for one sample in well M8, the fecal coliform counts were within the Florida bathing water standard of 200 cfu/100 mL, but above drinking water standards of 10 cfu/100 mL in many wells. At the Hickory campground, wells C6, S3, and S1 sporadically had counts between these two standards, as did the Magnolia wells M2, M3, M5, M6, M7, M8, M9, and M10. Wells S3 and M10 did show very low tracer, NO_3, and TP concentrations, which suggests that an additional source of fecal coliform, such as animal waste-contaminated surface water, is present.

4.6. Comparison of tracer velocities with previous studies

The velocities of 0.3 ± 0.2 m/day ($n = 11$) for SF_6 and 9.6 ± 10.5 m/day ($n = 11$) for fluorescein calculated in this study fall within the range of velocities from SF_6 tracer experiments in the Florida Keys, another karst environment. Dillon et al. (1999) report velocities ranging from 3 to 79 m/day, a second study reports velocities from 1 to 42 m/day (Dillon et al., 2000), and a third 0.3–19 m/day (Dillon et al., 2003). The large range of these velocities is indicative of a conduit flow component and complexity of groundwater transport in karst environments. Larger conduits and a deeper water table characterize the Ocala limestone at Manatee Springs compared to the Key Largo limestone in the Florida Keys. These differences allow for a greater degree of degassing in the Ocala limestone and are likely the reason only pM concentrations were observed in this study compared to nM concentrations in the Florida Keys studies despite similar injection concentrations.

Tracer studies using SF_6 and fluorescein have been performed in non-karst environments with uniform sandy soils in Florida, namely a barrier island (Corbett et al., 2000) and adjacent to seasonally inundated areas (SIAs) (DOH, 2002; Harden et al., 2003). Transport velocities, for SF_6 in these non-karst environments, are similar to the SF_6 velocities from this study, 0.3 ± 0.2 ($n = 11$). In the SIA study, the travel velocities for SF_6 were approximately 0.3 m/day (DOH, 2002; Harden et al., 2003) and 0.2 m/day at St. George Island (Corbett et al., 2000). Fluorescein velocities of 0.05 m/day in the SIA study (Harden et al., 2003) and 0.2 m/day in the barrier island study were observed.

Matrix flow is dominant in the SIA and barrier island environments.

4.7. Monitoring well network design

The results of this study allow an assessment of the monitoring strategy employed. Wells were installed to allow interception of likely flow paths based on surface water features and shallow geophysical investigations. At Magnolia, a riverfront site, tracer tests indicated that nearly all wells had a direct connection to the drainfield. In contrast, at the Hickory site, above an identified large cave system, tracer did not arrive in large concentrations at the wells that were towards the nearest surface water feature but was found only in the wells directly underneath and adjacent to the drainfield. This suggests that the water followed a path of least resistance downward towards the cave (Roeder et al., 2005), although this may have been affected by the slug density. Nonetheless, these results point to the importance of depth as a third dimension in monitoring contamination.

5. Conclusions

The conclusion of this study is that the proximity and connectivity of the surficial soils to the underlying karst aquifer limit the ability of conventional OSTDSs to attenuate nitrogen concentrations and allow rapid transport in the direction of the next surface water body or spring. The results strongly show that the use of conventional OSTDSs in karst environments has a negative impact on the surrounding groundwater quality for nitrogen, and to a lesser extent for TP.

The results of this study clearly showed great connectivity between the surficial soils and the underlying karst aquifer at both the Magnolia and Hickory sites. Tracer appeared within the wells in the early hours of the experiment. Tracer velocities ranged from 0.3 ± 0.2 m/day ($n = 11$) for the SF_6 data to 9.6 ± 10.5 m/day ($n = 11$) calculated from the fluorescein data.

While tracer and contaminant transport at the river site (Magnolia) occurred in shallow groundwater towards the river as expected, the transport pathway at the site on top of a large cave feeding a spring (Hickory) appeared to be downwards towards the cave. Such a possibility should be considered when designing or interpreting monitoring programs.

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