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PERFORMANCE EVALUATION OF IN-GROUND PASSIVE NITROGEN REDUCTION SYSTEM (PNRS)

Damann Anderson[1] and Josefin Hirst[2]

ABSTRACT

In 2009, the State of Florida initiated the Florida Onsite Sewage Nitrogen Reduction Strategies (FOSNRS) Project to develop more passive methods for nitrogen reduction from onsite wastewater systems (OWS). As part of the FOSNRS project, passive nitrogen reduction systems (PNRS) were developed, pilot tested, and evaluated at single family homes. The goal of these systems is to provide options for reducing nitrogen inputs to watersheds where OWS have been identified as a significant source of nitrogen.

Both in-tank and in-ground PNRS were developed and tested during this study. This paper presents results from the in-ground PNRS. Because of the flat topography common to the state, the definition of "passive" included the use of up to 1 pump as the only mechanical input to the system. The in-ground PNRS utilize a two-stage passive biofiltration concept treating septic tank effluent (STE). The first stage provides ammonification and nitrification via a porous media biofilter. The second stage provides denitrification via an anoxic biofilter with reactive media. Results from preliminary pilot testing of media led to development and testing of a prototype system. Results from the prototype system led to design and construction of a full scale single family home system. The full scale system included onsite reuse of the treated effluent for landscape irrigation. The in-ground system designs consisted of a vertically stacked media arrangement, with the Stage 1 biofilter directly above the Stage 2 biofilter, which was underlain by an impermeable liner.

The prototype and full scale in-ground PNRS were each monitored over an 18 month period, receiving STE with an average total nitrogen concentration of 65.4 mg N/L for the prototype system and 50.5 mg N/L for the full scale system. The average total nitrogen concentration of the treated effluent prior to subsurface dispersal was 3.5 mg N/L for the prototype system and 1.9 mg N/L for the full scale system, representing a 95% and 96% reduction in nitrogen concentration, respectively. At the full scale site, groundwater quality was monitored before and after the PNRS installation and results showed significant improvement in groundwater nitrogen concentrations after PNRS installation. These results suggest the potential to significantly reduce N input to sensitive watersheds from OWS.

BACKGROUND

The Florida Department of Health (FDOH) estimates that over 2.7 million onsite wastewater systems (OWS) are currently operating in the State of Florida. Nitrogen loading from onsite systems is a potential concern in the state, depending on the number and density of onsite installations, their proximity to receiving waters, nitrogen removal processes in subsurface soils and the sensitivity of receiving waters. The great majority of Florida onsite systems are comprised of a septic

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tank for primary treatment followed by dispersal into the environment using soil treatment units (STUs) commonly referred to as drainfields. Provided these typical systems meet current code requirements, they provide significant treatment of primary effluent, but their ability to remove nitrogen prior to the renovated effluent reaching groundwater is limited relative to other parameters. In 2008 the Florida legislature provided funding to FDOH to develop cost-effective, passive strategies for nitrogen reduction that complement the use of conventional OWS, and the Florida Onsite Sewage Nitrogen Reduction Strategies (FOSNRS) project was initiated in 2009. The FOSNRS project implemented a multi-pronged approach to address nitrogen loading from OWS to the Florida environment.

The FOSNRS project included an evaluation of nitrogen reduction options for OWS, followed by the development and testing of pilot-scale passive nitrogen reduction systems (Hazen and Sawyer and AET, 2014). For the purposes of this study, passive nitrogen reduction systems (PNRS) were defined as treatment technologies that utilize no more than one pump, no aerators or blowers, and a reactive media for denitrification. Reactive media were defined as supplemental materials that would act as electron donors in the passive denitrification process. Previous studies had indicated that a two-stage biofiltration process was effective for nitrogen reductions from OWS (Rich, 2007; Smith, Otis, and Flint, 2008; Smith, 2009a; Smith, 2009b; Smith, 2011). Lignocellulosic (woody plant materials) based media has been shown to be effective as reactive media for heterotrophic biological denitrification (Robertson and Cherry, 1995; Long, 1995; Robertson, Blowes et al., 2000; Schipper and Vodvodic-Vukovic, 2001; Dupuis, Rowland et al., 2002; Loomis, Dow et al., 2004; Robertson, Ford et al., 2005; EPA, 2007; Rich, 2007; Vallino and Foreman, 2007; Schipper, Cameron, and Warneke, 2010). Additionally, elemental sulfur has been shown to be effective as reactive media for autotrophic biological denitrification (Flere and Zhang, 1998; Shan and Zhang, 1998; Koenig and Liu, 2002; Nugroho, Takanashi et al., 2002; Zhang, 2002; Kim, Hwang et al., 2003; Zhang, 2004; Zeng and Zhang, 2005; Sengupta and Ergas, 2006; Sengupta et al., 2007; Smith, Otis, and Flint, 2008).

Based on the evaluation of nitrogen reduction options, several two-stage in-tank PNRS were pilot tested and performed very well, achieving over 90% TN reduction in the best performing configurations (Hirst et. al., 2014). The two-stage process consisted of an aerobic, unsaturated porous media biofilter for nitrification (stage 1), followed by an anoxic, saturated reactive media biofilter for denitrification (stage 2). The pilot testing was followed by development, design, construction and monitoring of full scale in-tank PNRS, and these in-tank systems also achieved TN reductions of over 90% (Hirst et. al., 2015, this conference).

While the two stage in-tank PNRS performance was excellent, the installation complexity and cost of the systems for existing home sites was higher than desired. In-ground systems were therefore considered as a way to potentially reduce system construction complexity and costs at existing homes. It was desired to develop an in-ground system that could be constructed much like a soil treatment unit, and the conceptual ideas revolved around a vertically stacked PNRS, where the stage 1 biofilter was placed over the stage 2 biofilter, with a liner used to saturate the stage 2 media and collect the treated effluent. The design, construction and performance of prototype and full scale in-ground systems is the subject of this paper.

MATERIALS AND METHODS

Stacked Media Testing: To test the in-ground, stacked stage 1/stage 2 media concept prior to development of the prototype system, several pilot units were set up to evaluate stacked media performance. Figure 1 provides a schematic of one of several pilot units constructed to test the concept, and determine if nitrification media over reactive denitrification media could provide sufficient nitrogen reduction. These pilot units were constructed in tanks to provide ease of testing and sampling, and were used for initial evaluation of stacked media for the in-ground concept. Figure 1 shows a test unit with 12 inches of sand stage 1 media underlain by stage 2 media consisting of 12 inches of a 60/40 expanded clay/lignocellulosic mixture (Stage 2a) and 4 inches of elemental sulfur at the bottom of the tank (Stage 2b). Southern yellow pine sawdust was used as the lignocellulosic reactive media. The level of saturation in the tank could be adjusted by raising or lowering the outlet elevation.

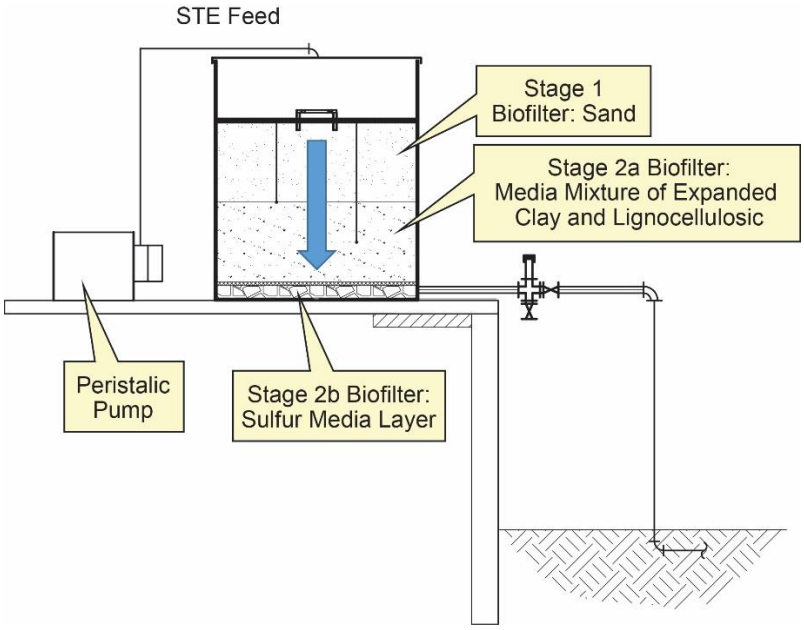


Figure 1. Typical schematic of pilot units used for stacked stage1/stage2 media testing

Media testing in the pilot units indicated that nitrification in the stage 1 media was followed by denitrification in the stage 2 media, as expected. For an STE concentration of 52.5 mg N/L applied to sand stage 1 media, total nitrogen reductions of 50 – 80% were achieved through the stage 2a expanded clay/sawdust mix, with reductions of 60 – 95% through the lower stage 2b sulfur media prior to discharge. Further details of these studies can be found in Hazen and Sawyer and AET (2014). While the stacked stage 1/stage 2 media concept showed promise, the limiting factor in these results was nitrification, which was often limited in the upper stage 1 media. It was suspected that nitrification was hampered by placement of the media in a tank, with saturation present in the lower levels, limiting oxygen for the nitrification reaction. It was felt that the actual in-ground units could be designed to eliminate this limitation and provide better nitrification efficiency.

Prototype In-ground PNRS: Based on the results from the media testing, a prototype in-ground PNRS was designed and constructed at the OWS test facility at the University of Florida Gulf

Coast Research and Education Center (GCREC) for more thorough testing. The site for this prototype unit consisted of a somewhat poorly drained fine sandy soil, and wet season water table elevations required a mounded system be designed. The mound system design consisted of 18 inches of fine sandy soil media for the stage 1 biofilter placed over a 50/50 mixture of sand and southern yellow pine sawdust lignocellulosic media in a V-shaped liner (stage 2a). An effluent collection pipe ran along the center of the liner, and discharged the stage 2a effluent to a small upflow stage 2b biofilter containing elemental sulfur reactive media mixed with oyster shell for further denitrification as necessary. Oyster shell is used for alkalinity control for the autotrophic denitrification process. The final effluent from the system was discharged to an infiltration trench consisting of plastic chambers. Figure 2 shows a schematic of the prototype in-ground PNRS that was constructed and monitored as part of the FOSNRS project.

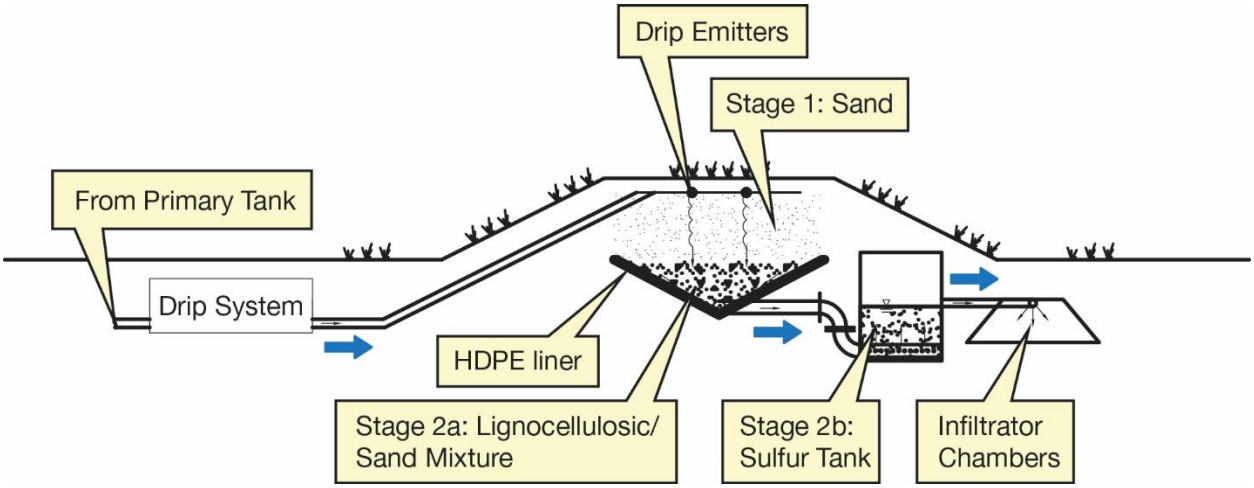


Figure 2. Schematic of the prototype in-ground PNRS constructed at the GCREC test facility (not to scale)

Full Scale In-ground PNRS: Based on the results from the prototype in-ground system, a full scale in-ground PNRS was designed and constructed for a 5 bedroom single family home in Seminole County, Florida. A process flow schematic for this system is provided in Figure 3. Similar to the prototype systems, this system also included two separate stage 2 biofilters for evaluation, a lignocellulosic mixture (stage 2a) in the liner underlying the stage 1 biofilter and a saturated upflow elemental sulfur biofilter in a tank (stage 2b). Wood chips mixed with sand were used as the lignocellulosic reactive media in stage 2a. Tankage and equipment for the full scale in-ground PNRS consisted of a 1,500 gallon two chamber concrete primary treatment tank; a 600 gallon concrete septic tank effluent (STE) dose tank; an above ground centrifugal pump; a two zone Perc-Rite™ drip application system; and a 1,050 gallon concrete tank enclosing the Stage 2b saturated upflow sulfur media biofilter.

To meet the "passive" requirement, the above ground centrifugal pump system was designed to allow a single pump to draw STE from the dose tank or treated effluent from the stage 2b biofilter tank, and pump either source to the 2-zone drip system hydraulic unit. A control system automatically switched from STE to treated effluent in alternating doses, with STE being directed to drip zone 1 and treated effluent being directed to drip zone 2. The first zone of the drip system applied primary effluent (STE) to the root zone of turf grass on top of the Stage 1&2a

lined biofilter, which consisted of fine sandy soil (Stage 1) overlying a 50/50 mixture of sand/wood chips (Stage 2a). This was installed on a sloped impermeable liner with an underdrain for effluent collection that discharged to the Stage 2b sulfur biofilter tank. The stage 2b media consisted of a 90/10 mixture of sulfur/oyster shell. The second zone of the drip system applied final treated effluent from the Stage 2b tank as reclaimed water for irrigation of the homeowners landscape.

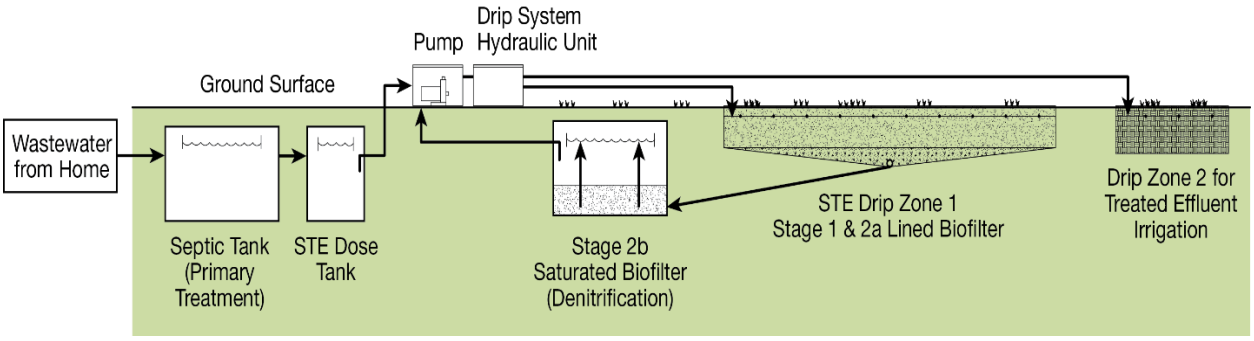


Figure 3. Process flow schematic for the full scale in-ground PNRS constructed and tested at a single family home (flow schematic only, not to scale)

Water Quality Monitoring: Water quality samples from both in-ground systems were collected to evaluate the primary tank effluent (STE), Stage 1 effluent, and Stage 2a and 2b effluent for water quality analysis. Sample collection, handling and analyses methods were in accordance with Florida Department of Environmental Protection Standard Operating Protocols. A peristaltic pump was used to collect samples and route them directly into analysis-specific containers, with appropriate preservatives, after sufficient flushing of the tubing had occurred. Field parameters were then recorded. Routine QC checks were performed of sampling and analysis procedures for both field QC samples and laboratory QC samples. The number of QC samples collected was approximately 10 percent of the total number of samples collected in the overall monitoring. Field QC samples included field blanks, equipment rinsates, and duplicates.

Chain of custody forms were used to document the transfer of samples from field personnel to the analytical laboratory. All analyses were performed by independent and fully NELAC certified analytical laboratories. Table 1 lists the analytical parameters, analytical methods, and detection limits for laboratory analyses. Field parameters were measured using portable electronic probes and included temperature (Temp), dissolved oxygen (DO), oxidation-reduction potential (ORP), pH, and specific conductance.

Table 1. Analytical parameters, method of analysis, and detection limits

Analytical Parameter	Method of Analysis	Method Detection Limit (mg/L)
Total Alkalinity as $CaCO_3$	SM 2320B	2 mg/L
Chemical Oxygen Demand (COD)	EPA 410.4	10 mg/L
Total Kjeldahl Nitrogen (TKN-N)	EPA 351.2	0.05 mg/L
Ammonia Nitrogen (NH_3-N)	EPA 350.1	0.005 mg/L

Nitrate Nitrogen (NO_3-N)	EPA 300.0	0.01 mg/L
Nitrite Nitrogen (NO_2-N)	EPA 300.0	0.01 mg/L
Nitrate+Nitrite Nitrogen (NOX-N)	EPA 300.0	0.02 mg/L
Total Phosphorus (TP)	SM 4500P-E	0.01 mg/L
Carbonaceous Biological Oxygen Demand ($CBOD_5$)	SM5210B	2 mg/L
Total Solids (TS)	EPA 160.3	.01 % by wt
Total Suspended Solids (TSS)	SM 2540D	1 mg/L
Total Organic Carbon (TOC)	SM5310B	0.06 mg/L
Sulfate	EPA 300.0	2.0 mg/L
Hydrogen Sulfide (unionized)	SM 4550SF	0.01 mg/L
Fecal Coliform (fecal)	SM9222D	2 ct/100mL
E.coli	SM9223B	2 ct/100mL

RESULTS AND DISCUSSION

Prototype In-ground PNRS: The prototype in-ground PNRS was monitored over a period of 523 days. The stage 1 biofilter had STE applied via drip irrigation at a rate equivalent to 0.8 gal/day/ft^2, which was the Florida code design rate for the fine sandy soil used in stage 1. The PNRS produced a mean final effluent $CBOD_5$ concentration of 14.3 mg/L, TSS of 7.2 mg/L, total nitrogen (TN) of 3.5 mg/L and fecal coliform count of 6.5 col/100ml over the study period.

Table 2 provides mean water quality results for the key study parameters by treatment process over the evaluation period. The primary treated (STE) influent to the system had mean total nitrogen concentration of 65.4 mg N/L, primarily as ammonia. The stage 1 biofilter was successful in fully nitrifying the STE, with a mean effluent ammonia concentration of 0.03 mg N/L and nitrate concentration of 33.13 mg N/L. It is notable that there was an approximately 44 percent reduction in total nitrogen concentration through the stage 1 biofilter alone. Mean total nitrogen concentration in the stage 2a effluent was 6.5 mg N/L, a 90% reduction from the STE concentration. This was reduced further by the stage 2b sulfur biofilter to 3.5 mg N/L, for a 95% overall nitrogen reduction by the system prior to discharge to the infiltration system trench. The system also consistently reduced fecal coliform bacterial counts to below 5/100 ml. through the stage 1 and 2a biofilters.

Figure 4 provides a time series of the nitrogen data collected from the prototype in-ground PNRS. The data shows consistent performance of the final system effluent despite considerable variations in STE nitrogen concentrations. The stage 2a sand/sawdust biofilter effluent averaged 6.5 mg N/L but varied between 3 and 15 mg N/L over the study. The stage 2b sulfur biofilter effluent averaged 3.5 mg N/L and was much more consistent in its performance, consistently below 7 mg N/L. These results illustrate the reliability that redundant stage 2 systems can provide if treatment performance is critical.

Full Scale In-ground PNRS: The full scale in-ground PNRS was also monitored over a 523 day period, from July 2013 to December 2014. The single family home served by the system was a large dwelling, requiring a design flow of 580 gal/day for the system. However, the home was occupied by 2 persons and averaged only 145 gal/day flow during the study. This resulted in an equivalent hydraulic loading rate of 0.2 gal/day/ft^2 for drip dispersal to the fine sandy soil used in the stage 1 biofilter.

Table 2. Mean water quality monitoring results for prototype in-ground PNRS over 523 days of operation

	n	TKN mg N/L	NH_3 mg N/L	NO_x mg N/L	TN mg N/L	Sulfate mg/L	Fecal Coliform (Ct/100 mL)	% TN Reduction
		mean	mean	mean	mean	mean	geomean	
STE Drip	8	65.1	55.60	0.29	65.4	40.6	59,834	
Stage 1 18" Sand	8	3.2	0.03	33.13	36.3	49.4	Non-detect	44%
Stage 2a ligno/sand	9	3.0	0.36	3.55	6.5	115.7	2.3	90%
Stage 2b sulfur tank	8	3.4	0.95	0.06	3.5	292.9	6.5	95%
DISPERSAL								

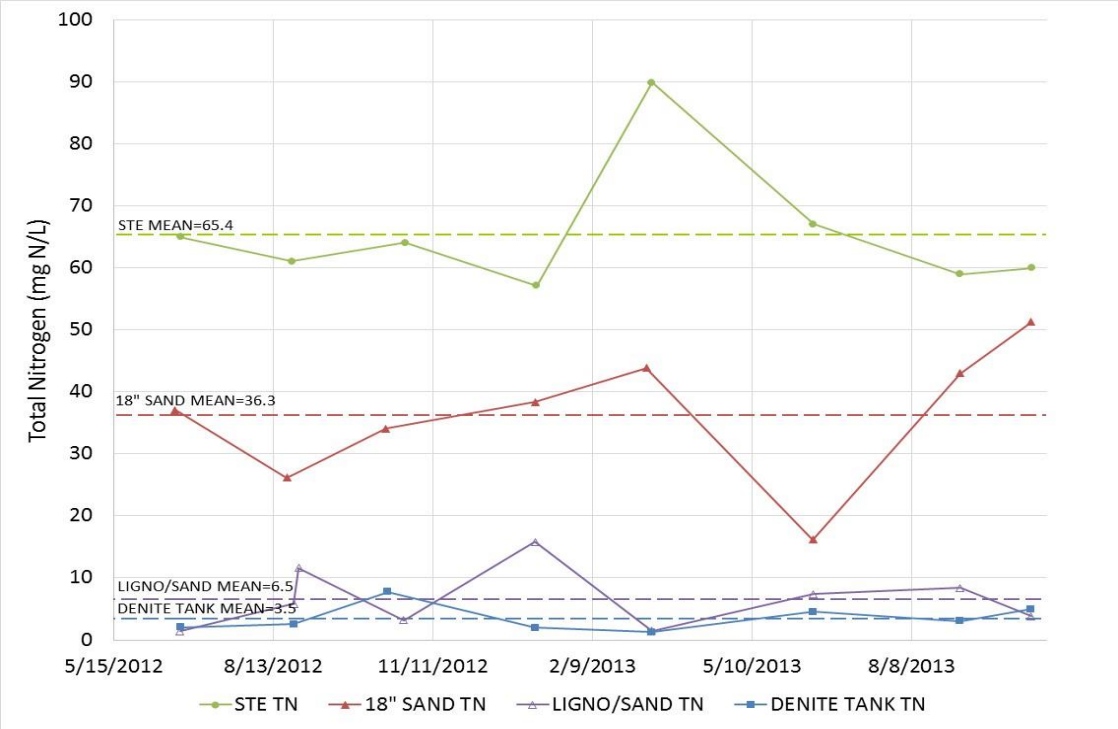
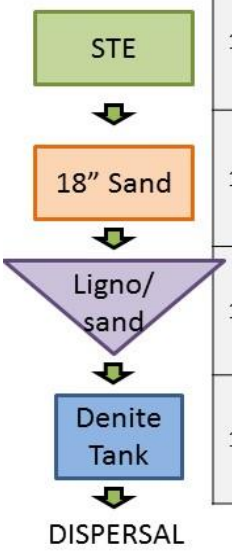


Figure 4. Time series of total nitrogen data from the prototype in-ground PNRS.

The primary treated (STE) influent to the full scale in-ground PNRS had a mean $CBOD_5$ concentration of 72 mg/L, TSS of 23 mg/L, TP of 5.1 mg/L, and total nitrogen concentration of 50.5 mg N/L, primarily as ammonia. The system produced a mean final effluent $CBOD_5$ concentration of 14.3 mg/L, TSS of 4.3 mg/L, TN of 1.9 mg/L, TP of 0.2 mg/L, and fecal coliform count of 5 col/100 ml over the study period. Water quality monitoring results by treatment process for key study parameters are presented in Table 3.

The stage 1 biofilter consistently nitrified STE, with ammonia concentration in the stage 1 effluent averaging 0.1 mg N/L. Mean total nitrogen concentration from the stage 1 biofilter was 25.4 mg N/L, primarily as nitrate nitrogen, and represented a 50% reduction in applied nitrogen concentration by the stage 1 biofilter alone. Total nitrogen in the stage 2a sand/lignocellulosic biofilter effluent averaged 7.9 mg N/L, representing an 84% decrease in nitrogen concentration from the applied STE. Approximately 5.8 mg N/L of the stage 2a effluent concentration was nitrate nitrogen. The stage 2a effluent flowed to the stage 2b sulfur biofilter where further nitrogen reduction took place. Stage 2b effluent total nitrogen averaged 1.9 mg N/L, representing a 96% reduction in total nitrogen concentration relative to the applied STE.

Table 3. Mean water quality monitoring results for the full scale in-ground PNRS over 523 days of operation



	n	TKN mg N/L		NH_3 mg N/L		NO_x mg N/L		TN mg N/L		Fecal Coliform (Ct/100 mL)		% TN Reduction
		mean	range	mean	range	mean	range	mean	range	mean	range	mean
STE	13	50.5	30-64	43.5	27-54	0.07	0.02-0.4	50.5	30-64	65,033	20,000-420,000	
18" Sand	13	2.1	1.0-4.9	0.1	0.01-1.6	23.3	1.3-47	25.4	2.5-51.6	1,000 (n=1)	1,000 (n=1)	50%
Ligno/ sand	13	2.1	0.9-4.2	0.2	0.04-0.7	5.8	0.02-14	7.9	1.0-16	32	Non-detect-6,800	84%
Denite Tank	13	1.3	0.8-1.8	0.3	0.02-0.9	0.6	0.02-5.3	1.9	0.84-7.1	5	Non-detect-300	96%

Fecal coliform counts were reduced to 5 col/100 ml in the PNRS effluent. The treated effluent from the full scale in-ground PNRS was reused for landscape irrigation at the home site via subsurface drip irrigation. It is therefore important to note that the PNRS effluent concentrations would likely be further reduced from plant uptake and soil infiltration in the landscape.

Figure 5 provides a time series of the full scale PNRS total nitrogen data. These results show a consistent reduction in total nitrogen through the stage 1 biofilter over the study period. Similar to the prototype in-ground PNRS, the stage 2a effluent nitrogen is more variable than the stage 2b effluent. The stage 2a biofilter effluent concentration averaged 7.9 mg N/L but ranged from 1 – 16 mg N/L. The stage 2b biofilter effluent concentration averaged 1.9 mg N/L, and ranged from 1 – 7 mg N/L, with only one sample above 5 mg N/L. Overall, the full scale in-ground PNRS provided highly treated effluent to the irrigation reuse system.

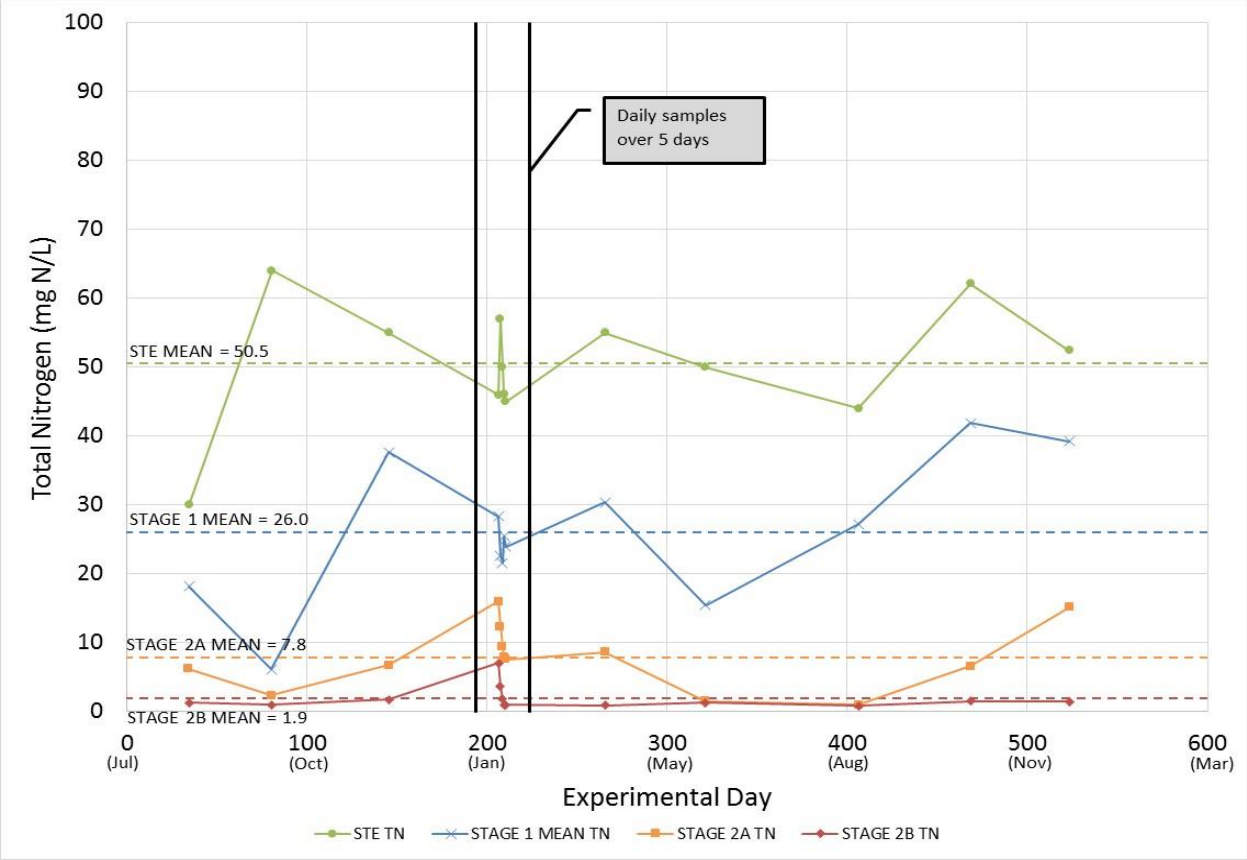


Figure 5. Time series of nitrogen data from the full scale in-ground PNRS

GROUNDWATER QUALITY

In addition to the treatment performance, groundwater quality was monitored at the full scale in-ground PNRS site before and after installation of the PNRS. Prior to the PNRS installation, a

groundwater monitoring network was established, which included over 60 groundwater monitoring wells down gradient of the home's existing conventional OWS drainfield. Figure 6 shows a plan view of the nitrogen plume based on maximum TN concentrations at all locations where groundwater samples were obtained during the four sample events (July 2011 through July 2012) taken prior to the full scale in-ground PNRS installation. In addition, illustrated in Figure 6 are two transect cross sections through the nitrogen plume, transects A-A' and B-B'. As the figure shows, shallow groundwater total nitrogen concentrations as high as 40 mg/L, primarily as NO_3-N, were measured at several locations just below and down gradient of the existing drainfield before installation of the PNRS.

For comparison, Figure 7 depicts the maximum TN concentration at all locations where groundwater samples were obtained during the sample event conducted 468 days following full scale PNRS start-up (Oct. 23 and 24, 2014), along with similar transect cross sections A-A' and B-B'. As shown, a significant decrease in total nitrogen concentration in the groundwater plume down gradient of the PNRS system has occurred since full scale PNRS installation. Total nitrogen concentrations in the shallow groundwater were generally $\leq$ 5 mg/L, approaching background concentrations at the site. Thus, the PNRS appears to be greatly improving groundwater quality at this site.

OPERATION AND MAINTENANCE

Operation and maintenance of the in-ground PNRS was minimal after an initial start-up period where system settings were established. The drip dispersal hydraulic system and controls required the most attention and will require routine operational visits from trained personnel to keep systems up and running. For simpler operation and maintenance, conventional low pressure dosing systems could be used for stage 1 distribution, and this would greatly simplify these systems, but treatment performance may be impacted.

Power use for the full scale in-ground PNRS averaged approximately 1 kWh per day, or 7.8 kWh per 1000 gallons treated. This power use included the drip irrigation system for treated effluent reuse. For the home studied, this amounted to approximately $3.00 per month in power costs.

There was no indication of any reduction in the reactive media (lignocellulosic or sulfur) levels after approximately 18 months of operation, and initial observations and theoretical calculations suggest that the media will last for many years.

CONCLUSIONS

Results of the in-ground PNRS testing in the FOSNRS project indicate that consistent nitrogen reductions of over 90%, with total nitrogen effluent concentrations consistently under 10 mg-N/L are possible with a two-stage biofilter in-ground system as described herein. Groundwater monitoring results at the full scale in-ground PNRS site before and after installation suggest that significant improvement in near field groundwater quality could result from use of these systems. The results from the FOSNRS study suggest the potential to significantly reduce N input to sensitive watersheds from OWS by use of these passive nitrogen reduction systems.

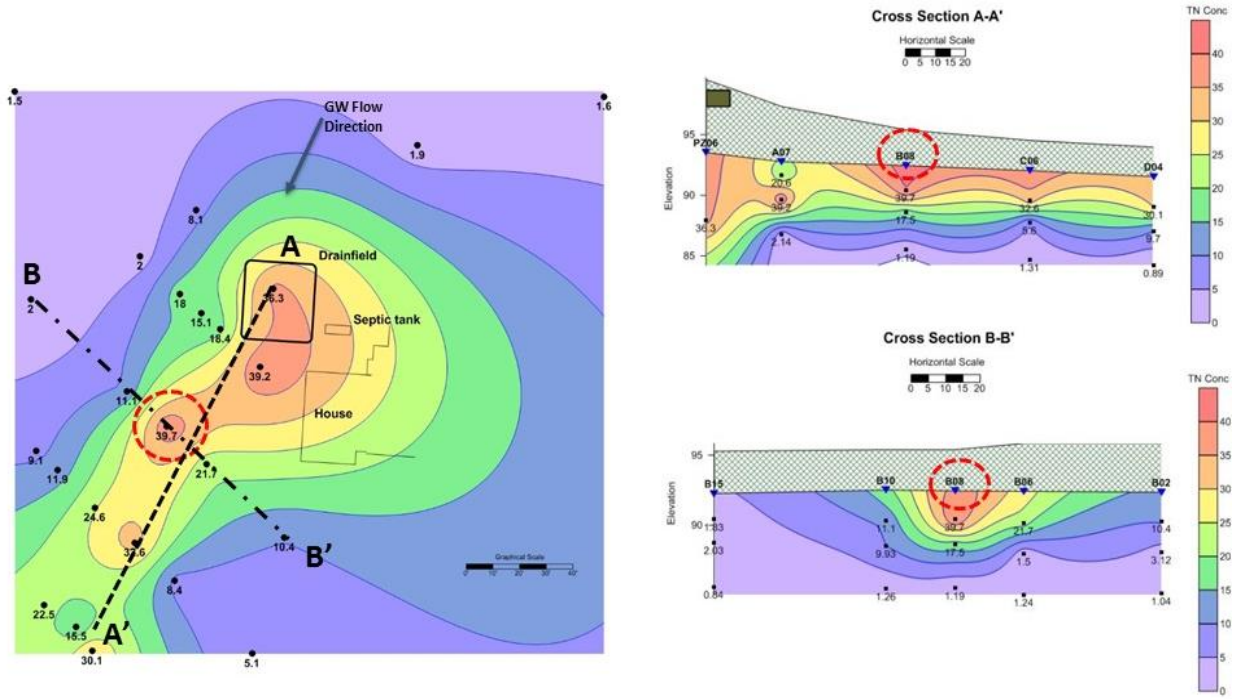


Figure 6. Groundwater total nitrogen concentrations down gradient of the conventional OWS prior to full scale in-ground PNRS installation

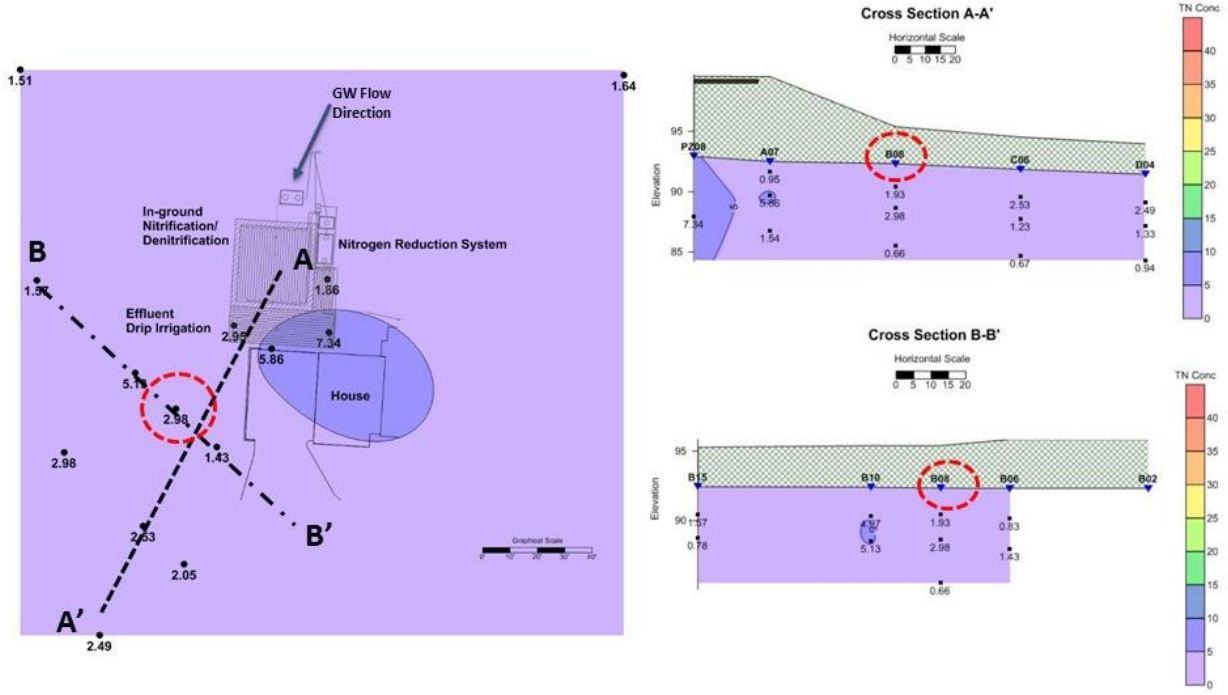


Figure 7. Groundwater total nitrogen concentrations 468 days following full scale PNRS start-up

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