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Distributed wastewater treatment offers an environmentally preferable alternative to conventional septic systems in Central Florida

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ABSTRACT

Wastewater management is a critical issue globally. In Florida, the importance of this issue is heightened by the proximity to sensitive ecosystems. Distributed wastewater treatment units (DWTU) are a recent, state-approved alternative to septic system conversions to centralized sewer infrastructure. In this study, the performance of a DWTU was tested at a new residence in Lake Hamilton, FL. A monitoring well was installed downgradient of the DWTU absorption field to establish baseline groundwater conditions prior to occupation of the residence. The residence was occupied, after which groundwater, DWTU influent, and effluent samples were collected. Many effluent parameters significantly decreased compared to influent, including ammonia (NH_3; 97%), total Kjeldahl nitrogen (TKN; 95%), total nitrogen (TN; 88%), the TN:TP ratio (84%), fecal coliforms (92%), carbonaceous biochemical oxygen demand (CBOD; 96%), and total suspended solids (TSS; 96%). In the groundwater, nutrient concentrations initially increased compared to the baseline data, but eventually decreased, demonstrating that the DWTU was effective at improving quality of wastewater effluent. These systems could be especially effective in sensitive areas where advanced wastewater treatment has been mandated or is needed.

Key words: fecal coliforms, groundwater, nutrients, nitrogen, wastewater, water quality

HIGHLIGHTS

- A distributed wastewater treatment unit was installed and studied at a residence in Florida.
- The distributed wastewater treatment unit significantly improved water quality of the residential wastewater effluent.
- 97% of ammonia, 88% of TN, and 92% of fecal coliforms were removed from effluent.
- Downgradient groundwater quality was better protected from wastewater contamination.

1. INTRODUCTION

Wastewater management is a globally important issue because inadequately treated domestic wastewater can have negative impacts when released into the environment. For example, increased nutrient loading from wastewater can promote harmful algal blooms (HABs) and eutrophication (Anderson *et al.* 2002; Anderson 2009; Nixon 2009; Lapointe *et al.* 2015, 2017; Paerl *et al.* 2018; Brewton *et al.* 2022). Further, wastewater can increase fecal pollution and pathogen loading to surface waters (Lipp *et al.* 2001a), especially during times of increased precipitation (Lipp *et al.* 2001b). Thus, it is critically important to reduce or eliminate untreated domestic wastewater flows into the environment.

In Florida, septic systems are widely used for on-site wastewater management, as regulated by Florida Administrative Code 62-6.002 (*formerly 64E-6.002*). However, many locations are not appropriate for this method due to sandy, karstic, or porous soils, often with seasonally high water tables and high population densities (Bicki *et al.* 1984; Bicki & Brown 1990, 1991; Lapointe *et al.* 2017; Herren *et al.* 2021; Brewton *et al.* 2022). As such, septic systems often contaminate groundwater and surface waters in Florida with excessive nutrients and bacteria (Lapointe *et al.* 1990; Aravena *et al.* 1993; Lapointe & Krupa 1995; Corbett *et al.* 2002; Lapointe *et al.* 2015, 2017; Herren *et al.* 2021; Brewton *et al.* 2022). This contamination is a critical issue because there are many sensitive aquatic habitats throughout Florida, including coral reefs in the Florida Keys and Southeast Florida, seagrasses in estuaries such as the Indian River Lagoon and the Caloosahatchee River Estuary, and freshwater springs. All these ecosystems support threatened and/or endangered species, so improving and maintaining water quality by improving wastewater management in these areas is paramount.

Alternative methods can be used to treat wastewater on site. For example, distributed wastewater treatment (DWT) represents new technology for wastewater management that was recently approved by the Florida Department of Environmental Protection (FDEP). This study was designed to test the *in situ* performance of an FDEP-permitted and recently installed DWT unit (DWTU) in the Town of Lake Hamilton located in central Florida. The goal of this study was to assess changes in wastewater effluent attributable to the DWTU and to monitor downgradient groundwater for associated changes.

2. METHODS

2.1. Description of the DWTU

The DWTU evaluated in this study is manufactured by OnSyte Performance, LLC (OnSyte) and authorized by a FDEP permit issued to the Town of Lake Hamilton (Polk County), Florida. An OnSyte DWTU is similar in size to a septic tank, but the wastewater treatment process is similar to a municipal treatment plant, utilizing a three-chambered, suspended-growth, activated-sludge, automated sequencing batch reactor (SBR) process controlled by an onboard computer (Figure 1). The maximum treatment capacity of the OnSyte residential DWTU is 825 gallons per day (GPD; 3,123 L/day) and it is designed to achieve peak treatment efficiency at an average flow of 300 GPD (1,136 L/day), which is typical of a single-family residence in Florida.

To maximize nitrogen (N) removal, aeration and denitrification are optimized through real-time flow monitoring and computer-controlled recirculation within the SBR. Each DWTU consists of three separate chambers (Figure 2; Table 1). The first chamber is 430 gallons (1,628 L) and used for primary sedimentation (settling) and digestion of biosolids. The wastewater flows (via gravity) from the first chamber into a 410-gallon (1,552 L) flow equalization and dosing chamber. The onboard computer continuously monitors the liquid level in the dosing chamber and determines an appropriate treatment batch volume based on incoming flows (calculated based on the rate of change in liquid level). The computer then pumps a 'batch' of wastewater from the dosing chamber into the 400-gallon (1,514 L) reaction chamber, where biological treatment is provided in a sequential, computer-controlled aeration, mixing and clarification process.

After each batch is completed, the onboard computer selects a variable fraction of the treated batch for additional treatment via internal recycling. This fraction of fully treated effluent is pumped back to the first (settling) chamber, diluting the incoming wastewater and receiving additional treatment (Figure 1). The remaining fraction of each treated

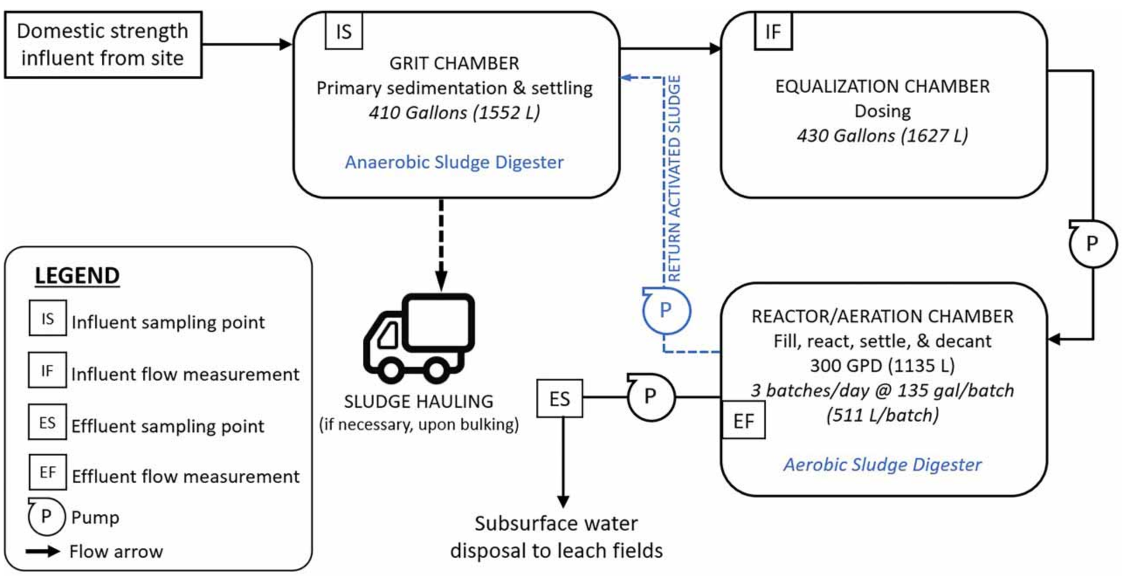

Figure 1 | Process flow diagram of OnSyte Distributed Wastewater Treatment Unit (DWTU).

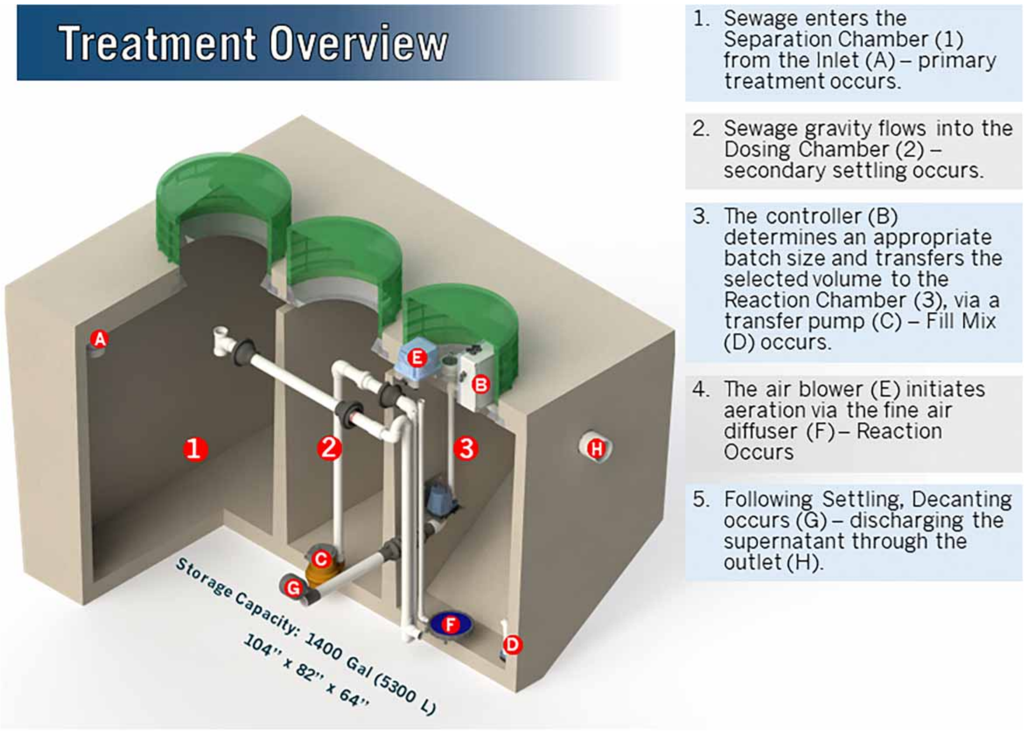

Figure 2 | DWTU cutaway and treatment overview.

Table 1 | DWTU equipment details

Process/Equipment	Description	Requirement
Oil and Grease Separator, Grit Tank & Primary Sedimentation	430 gallons (1,628 L)	28 day holding between pump outs
Dosing Tank	410 gallons (1,552 L)	2 hrs holding at PHF
Transfer Pump	1/4 HP, 30 gpm (113 LPM)	Transfer batch in 15 minutes or less
Reactor Tank	400 gallons (1,514 L)	8-hour batches at ADF 2-hour batches at PHF
Blowers	1 Linear air pump @ 150 LPM, 5.3 cfm	
Waste Pump	1/6 HP, I8 gpm (68 LPM}	
Decanting Pump	1/6 HP, I8 gpm (68 LPM)	30-minute decant with floating flextube to ensure only discharge of supernate
Land Application	Absorption drainfield	$<3''$/day

batch of effluent is discharged via pump to the drainfield. Finally, the DWTU utilizes a return activated sludge process to optimize sludge volume in the reaction chamber and minimize accumulation of biosolids in the settling chamber. Activated sludge is periodically 'wasted' (returned by pump) to the settling chamber where biosolids are broken down via anaerobic digestion.

All DWTU treatment processes are performed by an onboard computer and remotely monitored using a Supervisory Control and Data Acquisition (SCADA) system. The SCADA system communicates with each DWTU over a wireless data (cellular) network and records wastewater treatment volume and flow, component run time and power consumption (approximately 1.3 kWh per day), and equipment deficiencies; performs diagnostics; and enables remote supervisory control by a licensed wastewater operator. All system data collection, performance monitoring, and supervisory control is cloud-based, with redundant storage for data protection and information security measures to ensure access is restricted to authorized users. If a DWTU has a mechanical or process failure, technicians are notified, and the problem is resolved. Approximately every 7–10 years or as required, the biosolids residuals must be removed from the DWTU by a licensed contractor for treatment and disposal.

2.2. Study site and well installation

The DWTU study site was located at 1045 West Main Street, Lake Hamilton, FL (Permit Number FLAB07110, issued April 27, 2020; Figure 3(a)). Before the construction of a three-bedroom, single-family residence with a new DWTU and subsurface absorption field, the property was vacant and there are indications of agricultural use prior to 2000. A location in the public right of way on the north side of West Main St. that was less than 10 feet (~3.1 m) downgradient from the subsurface absorption field was selected for installation of a groundwater monitoring well (Figure 3(a)). The monitoring well was located away from external groundwater quality influences, such as nearby septic systems. The groundwater flow was in a southerly direction, towards a depressional wetland (Figure 3(b)).

At this location, a single groundwater monitoring well with a depth of ~12′ (~3.7 m) was installed using an auger on September 21, 2020. The well installation report classified the sediment at the site to be fine-grained sand and the well was constructed to the following specifications:

(a) 2-in diameter Schedule 40 PVC monitoring well casing set in an 8-in borehole;
(b) The well was cased from 0–2’ (~0.61 m) and was screened from 2-12’ (~0.61 m – ~3.7 m);
(c) Silica sand (gradation 20/30) filter pack was placed around the screen from the bottom of the borehole to approximately 1′ (~0.31 m) above the screen;
(d) A 1′ (~0.31 m) fine sand seal was placed above the sand filter pack;
(e) The well was sealed from the top of sand to ground surface with neat cement or bentonite/cement grout; and
(f) The wellhead was placed in flush mounted wellhead cover with a locking well cap.

Figure 3 | Study site in Lake Hamilton, FL, showing (a) aerial imagery of the residence where the DWTU and groundwater monitoring well were installed in Lake Hamilton, FL and (b) groundwater flow at the study site.

2.3. Study timeline

'Baseline monitoring' of existing groundwater conditions began on October 9, 2020, prior to the occupation of the home. This established and normalized any existing outside influences of groundwater quality. The residence was occupied on December 1, 2020 by a family of two persons, and wastewater flows recorded throughout the study were between 100 and 200 gallons per day, which falls within the typical range of residential wastewater flow (EPA Onsite Wastewater Treatment Manual, Table 2-3, 2002). The DWTU began operation 'dry' without seeding with activated sludge and the multi-pass program was initially disabled to prevent the dilution of the influent during the 'unit conditioning' phase. The DWTU was made 'fully operational' when the internal recycling process was activated in the treatment program on March 10, 2021. During the fully operational phase, wastewater influent was diluted with recycled wastewater and the effluent received additional treatment

Table 2 | Parameters of wastewater influent and effluent samples collected during a fully operational phase of the OnSyte DWTU that spanned from March 17 to June 30, 2021; showing mean ± standard error, the percent difference between influent and effluent, number of samples (*n*), and Mann Whitney U test *p* values for the comparison of influent and effluent with significant differences considered at $p<0.05$

Water Quality Parameter	Wastewater Influent	DWTU Effluent	Percent Difference	*n*	Mann Whitney U Test *p* value
Ammonia (mg/L)	73.69 ± 4.0	2.19 ± 2.1	−97	13	0.002
Nitrate + Nitrite (mg/L)	0.28 ± 0.02	8.91 ± 0.9	+3,071	13	<0.001
Total Kjeldahl Nitrogen (mg/L)	117.5 ± 4.7	5.34 ± 2.1	−95	13	0.017
Total Nitrogen (mg/L)	118.0 ± 4.7	14.2 ± 2.0	−88	13	<0.001
Total Phosphorus (mg/L)	19.42 ± 1.1	12.1 ± 0.75	−38	13	0.068
TN:TP	14.2 ± 0.64	2.32 ± 0.14	−84	13	0.030
Fecal Coliforms (CFU/100 mL)	45,138 ± 16,984	3,775 ± 1,782	−92	13	0.079
Carbonaceous Biochemical Oxygen Demand (mg/L)	410.8 ± 35.5	5.02 ± 0.67	−96	13	<0.001
Total Suspended Solids (mg/L)	304 ± 68	11.2 ± 1.6	−96	13	<0.001
Field pH	7.13 ± 0.1	6.98 ± 0.1	−2	11	1.000

Table 3 | Parameters of groundwater samples collected from a downgradient monitoring well in the Town of Lake Hamilton, FL by study phase

Water Quality Parameter	Baseline (*n*=5)	Unit Conditioning (*n*=10)	Fully Operational (*n*=15)	Vacated (*n*=5)	Reoccupied (*n*=1)	Kruskal-Wallis Test *p* value
Ammonia (mg/L)	0.035 ± <0.001	0.193 ± 0.13	0.035 ± <0.001	0.035 ± <0.001	0.035	<0.001
Nitrate + Nitrite (mg/L)	1.55 ± 0.28	27.0 ± 7.9	12.2 ± 0.96	0.35 ± 0.24	9.90	<0.001
Total Kjeldahl Nitrogen (mg/L)	0.81 ± 0.07	0.85 ± 0.47	0.97 ± 0.10	1.30 ± 0.13	2.10	0.059
Total Nitrogen (mg/L)	2.36 ± 0.34	27.8 ± 7.6	13.2 ± 0.91	1.65 ± 0.23	12.0	<0.001
Total Phosphorus (mg/L)	0.061 ± 0.007	0.067 ± 0.012	0.061 ± 0.005	0.29 ± 0.058	0.10	0.002
TN:TP	44.5 ± 6.6	1,099 ± 359	494 ± 37	16.6 ± 6.9	266	<0.001
Fecal Coliforms (CFU/100 mL)	1.09 ± 0.09	1.00 ± 0	0.92 ± 0.08	1.00 ± 0	1.00	0.568
Field pH	5.11 ± 0.16	5.35 ± 0.22	5.79 ± 0.23	5.64 ± 0.13	6.95	0.076
Turbidity	29.3 ± 6.1	20.6 ± 8.0	5.34 ± 1.1	176 ± 33	17.8	<0.001

Due to a lag between loading and groundwater effects the following timeframes were used. 'Baseline' groundwater monitoring occurred from October 9, 2021 to January 21, 2020, the 'Unit Conditioning' phase occurred from January 28, 2020 to April 1, 2021, and the DWTU was 'Fully Operational' from April 15, 2021 to June 30, 2021. The residence was vacated June 30 to September 3, 2021 and reoccupied on September 16, 2021. Also shown are *p* values from Kruskal-Wallace tests of study phases with significance considered at $p<0.05$.

(see section 2.1). The DWTU remained fully operational until the residence was vacated on June 30, 2021. After the occupants vacated the residence, groundwater was monitored in July 2021 to assess performance with 'no input'. The residence was reoccupied by a different family in early August 2021, after which monitoring continued until October 7, 2021 to assess the capacity of the DWTU to function after a 40-day dormant period with no wastewater inputs.

2.4. Water collection and laboratory analyses

Groundwater samples were collected by Pace Analytical Services, LLC, (Pace) staff with a peristaltic pump following FDEP groundwater sampling protocols and delivered to Pace, Oldsmar, FL or Tampa, FL (bacteria only) for analyses. Samples of wastewater influent and DWTU effluent were collected by OnSyte staff and sent to either Ackuritelabs, Inc. (AL), 3345 North Monroe St., Tallahassee, FL 32303 or Advanced Environmental Laboratories, Inc., (AEL) 380 North Lake Blvd., Suite 1048 Altamonte Springs, FL 32701 for the initial conditioning and fully operational phases. Between the time the first residents vacated the home on June 30, 2021 until the end of the study on October 7, 2021, influent and effluent samples were analyzed by OnSyte staff using a Hach DR3900 Spectrophotometer.

At Pace, AL, and AEL, samples were analyzed following standards methods approved by National Environmental Laboratories Accreditation Conference (NELAC). Wet chemistry methods included ammonia (NH_3; EPA 350.1), nitrate (NO_3^-) + nitrite (NO_2^-=NO_x; SM 4500), total Kjeldahl Nitrogen (TKN; EPA 351.2), total phosphorus (TP; EPA 365.4), total suspended solids (TSS; SM 2540D), pH (SM 4500H+B), and carbonaceous BOD (CBOD; SM 5210B). Fecal coliforms were analyzed using SM922D. Method detection limits (MDLs) at Pace were 0.035 mg/L for NH_3, 0.025 mg/L for NO_x, 0.086 mg/L for TKN, 0.050 mg/L for TP, and 1.0 MPN/100 mL for fecal coliforms. Method detection limits (MDLs) at AL were 0.066 mg/L for NH_3, 0.007 mg/L for NO_3^-, 0.004 mg/L for NO_2^-, 0.069 mg/L for TKN, 0.008 mg/L for TP, 2.0 mg/L for TSS, 0.1 for pH, 2.0 for CBOD, and 2.0 MPN/100 mL for fecal coliforms, while NO_x was calculated. Method detection limits (MDLs) at AEL were variable, but within range of the other laboratories. For the OnSyte tested samples at the end of the study period, the following Hach test kits were used: Ammonia TNT 832 (MDL 2–47 mg/L), Nitrate TNT 836 (MDL 5–35 mg/L), and Nitrite TNT 839 (MDL 0.015–0.600 mg/L).

2.5. Data handling and statistical analyses

DWTU data were categorized by the study phases described in section 2.3 for statistical analyses with slight differences between groupings for the DWTU and groundwater. For the DWTU analyses, the 'Unit Conditioning' phase (Cond) occurred from December 30, 2020 to March 10, 2021 and the DWTU was 'fully operational' (FO) from March 17 to June 30, 2021.

For groundwater, due to a lag between initial loading and observed effects, TN concentrations were used as indicators of change and the following timeframes were used to statistically assess groundwater impacts. 'Baseline monitoring' (BL) occurred from October 9, 2020 to January 21, 2021, the 'Unit Conditioning' phase (Cond) occurred from January 28, 2020 to April 1, 2021, and the 'fully operational' (FO) phase spanned April 15 to June 30, 2021. For groundwater analyses, the residence was considered vacated June 30 to September 3, 2021 (Vac) and reoccupied (ReOc) on September 16, 2021.

At HBOI-FAU, calculations were performed to determine concentrations of total nitrogen (TN=TKN+NO_x) and the molar ratio of TN to TP (TN:TP). All of the parameters were assessed by water type (groundwater, wastewater influent, and DWTU effluent) and study phase (baseline, DWTU conditioning, DWTU fully operational, residence vacated, and residence reoccupied). DWTU data for the vacated and the reoccupied phase were not statistically assessed, due to a change in the analytical methods (see section 2.3). Data were assessed for analysis of variance (ANOVA) assumptions. As assumptions were not met, characteristics of influent and effluent during the fully operational phase and groundwater for all phases were compared with a Kruskal-Wallis test (groups of three) or a Mann-Whitney U-test (groups of two) with significant differences considered at $p<0.05$. Significant comparisons for groups of three were followed by Dunn's test with a Bonferroni correction. Statistical analyses were conducted in SPSS v. 28.0 and figures were produced in Prism v. 9. Data are presented as single values or means with standard error (± S.E.).

3. RESULTS

3.1. DWTU performance

Nitrogen in the DWTU influent was dominated by NH_3, which comprised 63–75% of the TN. During the fully operational phase, the DWTU significantly (Mann-Whitney U test, $p=0.002$) reduced NH_3 concentrations 97% from influent to effluent (Table 2). Wastewater influent NH_3 concentrations were slightly higher in the conditioning phase (95.3 ± 6.6 mg/L) than in the fully operational phase (73.7 ± 4.0 mg/L) during which they were diluted with recycled wastewater (Figure 4(a)). Effluent

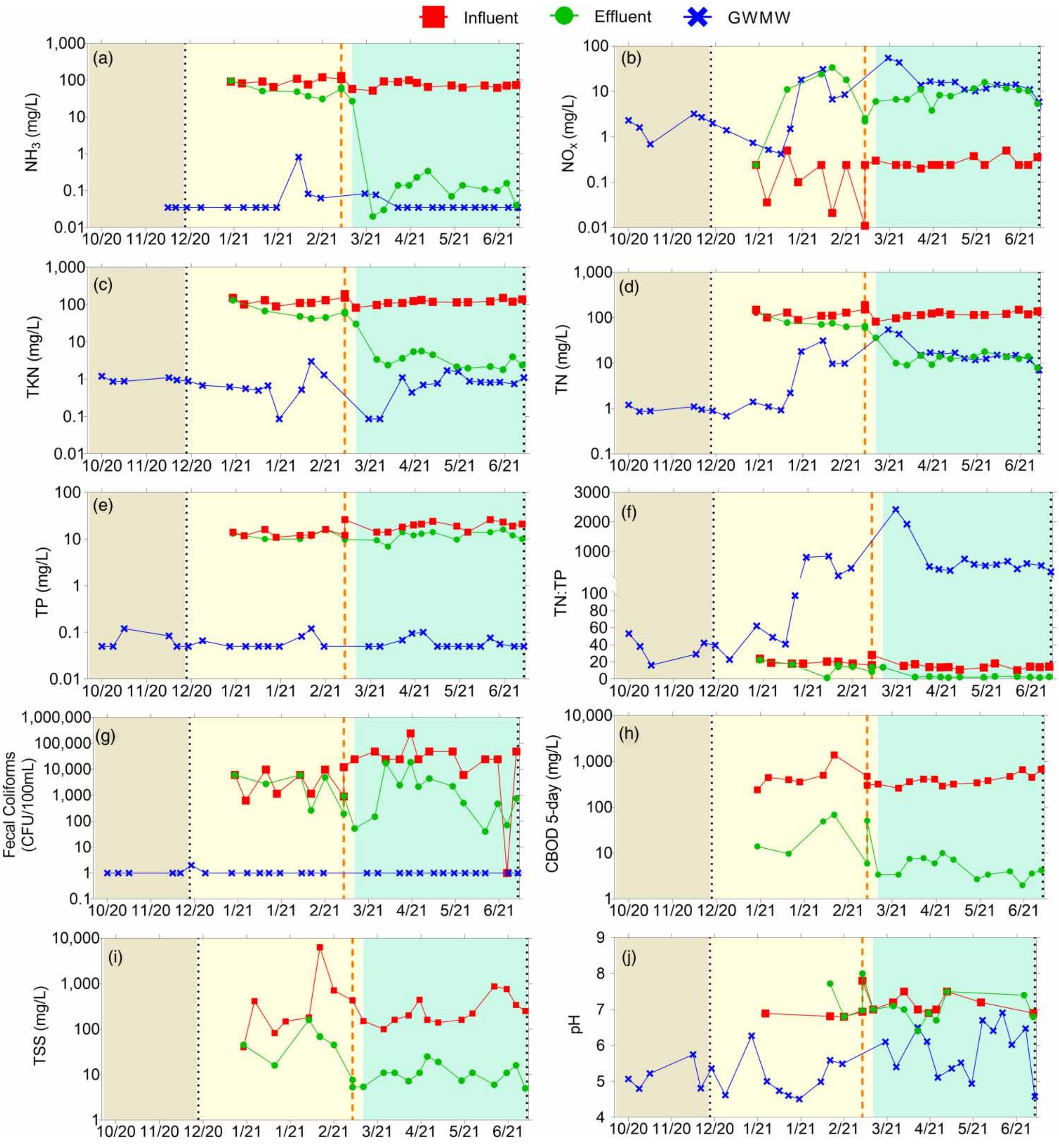

Figure 4 | Water quality parameters observed in wastewater influent (influent), an OnSyte DWTU effluent (effluent), and a downgradient groundwater monitoring well (GWMW) from October 9, 2020 through June 20, 2021, including (a) ammonia (NH_3), (b) nitrate+nitrite (NO_x), (c) total Kjeldahl nitrogen (TKN), d) total nitrogen (TN), (e) total phosphorus (TP), (f) the molar ratio of TN:TP, (g) fecal coliforms, (h) carbonaceous biochemical oxygen demand (CBOD), (i) total suspended solids (TSS), and (j) pH. Baseline groundwater monitoring occurred from October 9 to November 30, 2020, the 'unit conditioning' phase occurred from December 1, 2020 to March 10, 2021, and the DWTU was 'fully operational' from March 17 to June 30, 2021. Residence occupancy (December 1, 2020) and vacated (June 30, 2021) dates are indicated by black dotted lines, while the date the internal recycling feature was activated in the treatment program (March 10, 2021) is indicated by an orange dashed line.

from the DWTU had the highest NH_3 concentrations during the conditioning phase (46.8 ± 8.7 mg/L), which decreased sharply when the unit became fully operational (2.19 ± 2.1 mg/L). When the residence was reoccupied, influent had elevated NH_3 concentrations (40.1 ± 5.7 mg/L). Effluent during the reoccupied phase had NH_3 concentrations that were initially elevated (26.4 mg/L) and then sharply decreased to <2 mg/L.

As a result of the bacterial nitrification of NH_3 to NO_x, the DWTU significantly (Mann-Whitney U test, $p<0.001$) increased NO_x concentrations 3,071% from influent to effluent (Table 2). Wastewater influent NO_x concentrations were lower in the DWTU conditioning phase (0.16 ± 0.5 mg/L) than in the fully operational phase (0.28 ± 0.02 mg/L; Figure 4(b)). Effluent from the DWTU had the highest NO_x concentrations during the conditioning phase (14.2 ± 4.5 mg/L), which decreased when the unit became fully operational (8.91 ± 0.91 mg/L). When the residence was reoccupied, influent had moderate NOx concentrations (4.20 ± 2.5 mg/L) and NO_x concentrations in effluent remained <10 mg/L (9.46 ± 1.5 mg/L).

Similar to NH_3, the DWTU significantly (Mann-Whitney U test, $p=0.017$) reduced TKN concentrations 95% from influent to effluent (Table 2). Wastewater influent TKN concentrations were slightly higher in the DWTU conditioning phase (127.4 ± 9.5 mg/L) than in the fully operational phase (117.5 ± 4.7 mg/L; Figure 4(c)). Effluent from the DWTU had the highest TKN concentrations during the conditioning phase (55.5 ± 11 mg/L), which decreased sharply when the unit became fully operational (5.34 ± 2.1 mg/L).

The DWTU significantly (Mann-Whitney U test, $p<0.001$) reduced TN concentrations 88% from influent to effluent (Table 2). Wastewater influent TN concentrations were slightly higher in the DWTU conditioning phase (127.4 ± 9.5 mg/L) than in the fully operational phase (118.0 ± 4.7 mg/L; Figure 4(d)). Effluent from the DWTU had the highest TN concentrations during the conditioning phase (69.6 ± 10.4 mg/L), which decreased sharply when the unit became fully operational (14.2 ± 2.0 mg/L). For example, during the fully operational phase, effluent TN concentrations quickly dropped from 65.7 mg/L on March 10 to 36.0 mg/L on March 17 to 10.0 mg/L on March 30 (Figure 3(d)).

During the fully operational phase, the DWTU (Mann-Whitney U test, $p=0.068$) reduced TP concentrations 38% from influent to effluent, though this was not statistically significant (Table 2). Wastewater influent TP concentrations were lower in the DWTU conditioning phase (14.3 ± 1.4 mg/L) than in the fully operational phase (19.4 ± 1.1 mg/L; Figure 4(e)). Effluent from the DWTU had the highest TP concentrations during the conditioning phase (11.6 ± 0.66 mg/L), which remained similar when the unit became fully operational (12.1 ± 0.75 mg/L).

Because of greater removal of N than P, the DWTU significantly (Mann-Whitney U test, $p<0.001$) reduced molar TN:TP 84% from influent to effluent (Table 2). Wastewater influent TN:TP was slightly higher in the DWTU conditioning phase (20.13 ± 1.1) than in the fully operational phase (14.2 ± 0.64; Figure 4(f)). The DWTU effluent TN:TP was highest during the conditioning phase (13.5 ± 1.9) and decreased when the unit became fully operational (2.32 ± 0.14).

The DWTU significantly (Mann-Whitney U test, $p<0.001$) reduced fecal coliform concentrations 92% from influent to effluent (Table 2), but the results were highly variable. Wastewater influent fecal coliform concentrations were lower in the DWTU conditioning phase (4,829 ± 1,395 CFU/100 mL) than in the fully operational phase (45,139 ± 16,984 CFU/100 mL; Figure 4(g)). The internal recycling process, which was optimized for denitrification, also redistributed fecal coliforms throughout the internal chambers of the unit and complicated the analysis.

The DWTU significantly (Mann-Whitney U test, $p<0.001$) reduced CBOD concentrations 96% from influent to effluent (Table 2). Wastewater influent CBOD concentrations were higher in the DWTU conditioning phase (95.3 ± 6.6 mg/L) than in the fully operational phase (410.8 ± 35.5 mg/L; Figure 4(h)). Effluent from the DWTU had the highest CBOD concentrations during the conditioning phase (39.7 ± 9.2 mg/L), which decreased sharply when the unit became fully operational (5.02 ± 0.67 mg/L).

The DWTU significantly (Mann-Whitney U test, $p<0.001$) reduced TSS concentrations 96% from influent to effluent (Table 2). Wastewater influent TSS concentrations were higher in the DWTU conditioning phase (1,505 ± 303 mg/L) than in the fully operational phase (304 ± 68 mg/L; Figure 4(i)). Effluent from the DWTU had the highest TSS concentrations during the conditioning phase (50.0 ± 16 mg/L), which decreased sharply when the unit became fully operational (11.2 ± 1.6 mg/L). When the residence was reoccupied, influent had elevated TSS (190 ± 40 mg/L) concentrations. Effluent TSS concentrations were also initially elevated (47 mg/L), but then decreased to ~6.1 mg/L.

During the fully operational phase, the DWTU slightly reduced pH 2% from influent to effluent (Mann-Whitney U test, $p<0.001$; Table 2). Wastewater influent pH was lower in the DWTU conditioning phase (7.05 ± 0.2) than in the fully operational phase (7.13 ± 0.1; Figure 4(j)). Effluent from the DWTU was highest in pH during the conditioning phase (7.27 ± 0.3), which decreased when the unit became fully operational (6.98 ± 0.1).

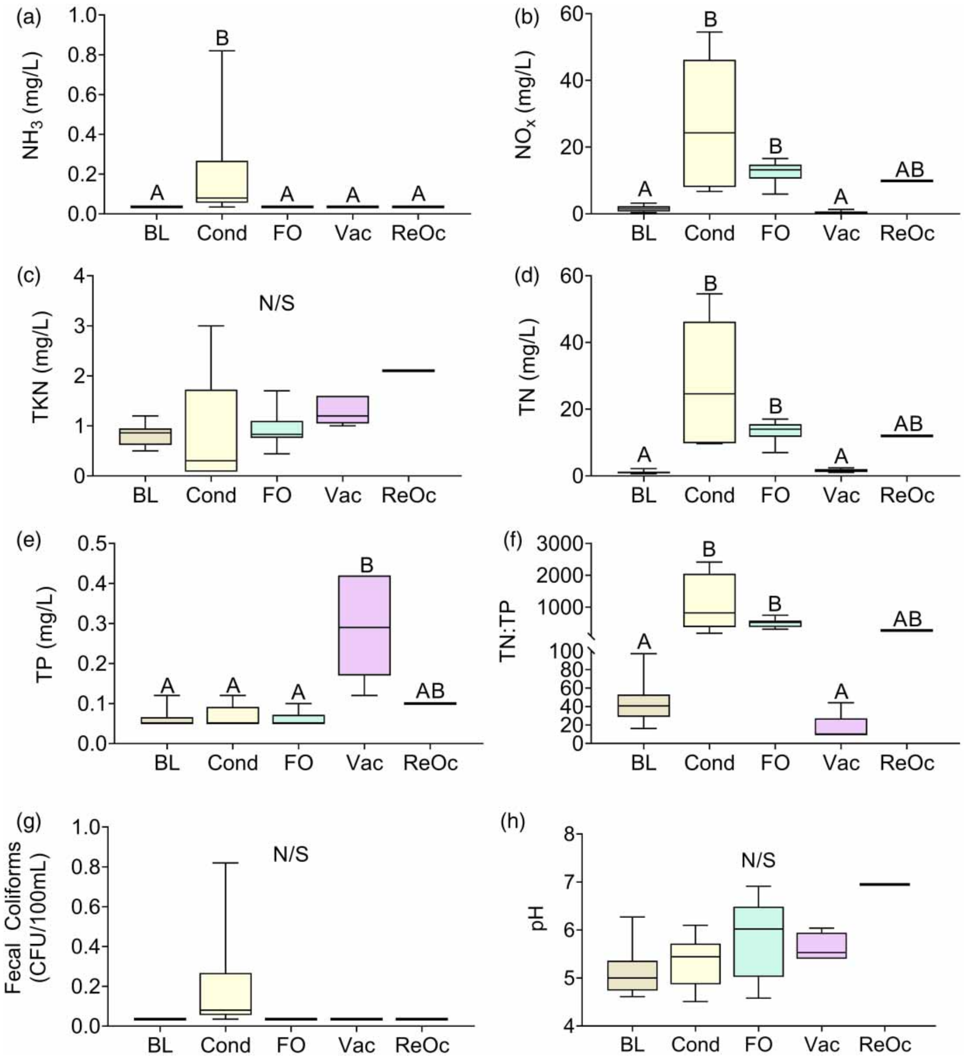

Figure 5 | Groundwater parameters observed in a downgradient monitoring well by study phase from October 9, 2020 through June 20, 2021, including (a) ammonia (NH_3), (b) nitrate+nitrite (NO_x), (c) total Kjeldahl nitrogen (TKN), (d) total nitrogen (TN), (e) total phosphorus (TP), (f) the molar ratio of TN:TP, (g) fecal coliforms, and (h) pH. Due to a lag between loading and groundwater effects the following timeframes were used. 'Baseline' (BL) groundwater monitoring occurred from October 9 to January 21, 2020, the 'unit conditioning' phase (Cond) occurred from January 28, 2020 to April 1, 2021, and the DWTU was 'fully operational' (FO) from April 15 to June 30, 2021. The residence was vacated June 30 to September 3, 2021 (Vac) and reoccupied (ReOc) on September 16, 2021. Significant differences ($p<0.05$) between study phases determined though Kruskal-Wallace tests followed by Dunn's test with a Bonferroni correction are represented by uppercase letters, while 'N/S' represents a non-significant comparison.

3.2. Groundwater

Once the DWTU was fully operational, concentrations of NH_3 in groundwater decreased significantly after a significant increase during the unit conditioning phase (Kruskal-Wallis test, $p<0.001$; Table 3). Baseline NH_3 concentrations in the groundwater were at the MDL of 0.035 mg/L (Figure 5(a)). During unit conditioning, the groundwater NH_3 concentration increased (0.193 ± 0.13 mg/L), peaking at 0.82 mg/L on February 11, 2021. After the DWTU was made fully operational, groundwater NH_3 concentrations decreased back to below MDL by April 15, 2021, where they remained for the duration of the study period.

Once the DWTU was fully operational, concentrations of NO_x decreased in groundwater, following a significant increase from the baseline during unit conditioning (Kruskal-Wallis test, $p<0.001$; Table 3). Baseline NO_x concentrations in the groundwater were 1.55 ± 0.28 mg/L (Figure 5(b)). While the DWTU was conditioning, the groundwater NO_x concentration increased to 27.0 ± 7.9 mg/L. Groundwater NO_x peaked on March 25, 2021 at 54.5 mg/L and then rapidly declined during the fully operational phase (12.2 ± 0.96 mg/L) to a low of 5.9 mg/L on July 30, 2021. NO_x decreased to baseline levels (0.35 ± 0.24 mg/L) when the home was vacated and then increased again when reoccupied (9.90 mg/L).

Groundwater TKN did not vary significantly over the study (Kruskal-Wallis, p=0.059), however continual increases were observed (Table 3). Baseline TKN concentrations in the groundwater were 0.81 ± 0.07 mg/L (Figure 5(c)). While the DWTU was conditioning, the groundwater TKN concentration increased slightly (0.85 ± 0.47 mg/L). Groundwater TKN concentrations continued to increase after the DWTU was made fully operational (0.97 ± 0.10 mg/L) and when the residence was vacated (1.30 ± 0.13 mg/L), peaking upon residence reoccupation (2.10 mg/L).

Concentrations of TN in groundwater decreased when the DWTU became fully operational, which followed a significant increase from the baseline during unit conditioning (Kruskal-Wallis test, p<0.001; Table 3). Baseline TN concentrations in the groundwater were 2.36 ± 0.34 mg/L (Figure 5(d)). After occupation of the home while the DWTU was conditioning, groundwater TN concentration increased to 27.8 ± 7.6 mg/L. TN concentrations peaked (54.5 mg/L) on March 25, 2021, after which they declined during the fully operational phase (13.2 ± 0.91 mg/L), achieving <7.0 mg/L on June 30, 2021. After the residence was vacated, groundwater TN concentrations were similar to the baseline (1.65 ± 0.23 mg/L) and then increased again when the residence was reoccupied (12.0 mg/L).

The groundwater had relatively low concentrations of TP throughout the study, which significantly increased when the residence was vacated (Kruskal-Wallis test, p=0.002; Table 3). Baseline TP concentrations in the groundwater were 0.061 ± 0.007 mg/L (Figure 5(e)). While the DWTU was conditioning, the groundwater TP concentration increased slightly (0.067 ± 0.012 mg/L). Groundwater TP concentrations peaked at 0.100 mg/L on April 28, 2021, after which they declined back to baseline concentrations of 0.05 mg/L by May 7, 2021. Therefore, during the fully operational phase, groundwater TP concentrations (0.061 ± 0.005 mg/L) were similar to the baseline. Interestingly, groundwater TP concentrations peaked again when the residence was vacated (0.29 ± 0.058 mg/L) and then decreased when the residence was reoccupied (0.100 mg/L). The slight increase in TP concentrations observed in the groundwater monitoring well may be a result of the effluent pooling and concentrating.

Groundwater molar TN:TP were variable throughout the study (Kruskal-Wallis test, p<0.001; Table 3). Baseline TN:TP in the groundwater were relatively low (44.5 ± 6.6). While the DWTU was conditioning, the groundwater TN:TP concentration significantly increased to very high values of 1,099 ± 359 (Figure 5(f)). Groundwater TN:TP peaked at 2,415 on March 25, 2021, after which it declined during the fully operational phase, but remained high (494 ± 37). When the residence was vacated, groundwater TN:TP significantly decreased (16.6 ± 6.9), and then increased again when the residence was reoccupied (266).

Low groundwater fecal coliform concentrations were observed with little variability throughout the study (Kruskal-Wallis test, p=0.568; Table 3). Baseline fecal coliform concentrations in the groundwater were 1.09 ± 0.09 CFU/100 mL (Figure 5(g)). Groundwater fecal coliform concentrations remained low, while the DWTU was conditioning (1.00 CFU/100 mL), during the fully functional phase (0.92 ± 0.08 CFU/100 mL), when the residence was vacated (1.00 CFU/100 mL), and reoccupied (1.00 CFU/100 mL).

Increased pH concentrations in groundwater followed operation of the DWTU, but the difference was not significant (Kruskal-Wallis test, p=0.076; Table 3). Baseline pH in the groundwater from November 20 to December 2, 2020 was 5.11 ± 0.16 (Figure 5(h)). While the DWTU was conditioning, the groundwater pH concentration was similar (5.35 ± 0.22). Once the DWTU was made fully operational, groundwater pH concentrations increased slightly (5.79 ± 0.23). Groundwater pH remained similar when the residence was vacated (5.64 ± 0.13) and then increased when the home was reoccupied (6.95).

Groundwater turbidity was significantly variable throughout the study (Kruskal-Wallis test, p<0.001; Table 3). Baseline turbidity in the monitoring well was 29.3 ± 6.1 NTU. During the conditioning phase, groundwater turbidity decreased to 20.6 ± 8.0 NTU and once the DWTU was made fully operational, a further decrease to 5.34 ± 1.1 NTU was observed. When the home was vacated, turbidity increased significantly (176 ± 33 NTU) and then decreased when reoccupied (17.8 NTU).

4. DISCUSSION

This study demonstrated that the OnSyte DWTU was highly effective at treating wastewater and protecting the ambient groundwater at a central Florida test site. This was evidenced by a high level of contaminant removal, especially N, from the wastewater stream and relatively minimal effects observed in the immediately downgradient groundwater monitoring well once the DWTU was fully operational. Considered together, these data support that the OnSyte DWTU may be an effective method for improving water quality in areas currently serviced by conventional septic systems or for new construction, especially near sensitive water bodies or in karst regions with vulnerable aquifer conditions. Indeed, compared with typical septic tank effluent concentrations of 140–200 mg/L BOD, 50–100 mg/L TSS, 40–100 mg/L TN, and 5–15 mg/L TP (US EPA 2002), the DWTU demonstrated significantly improved treatment performance.

During the fully operational phase, most of the parameters assessed in this study significantly decreased between the wastewater influent and the DWTU effluent. Additionally, effluent concentrations were also lower due to dilution with recycled wastewater during this phase. In particular, NH_3, TKN, CBOD, and TSS all decreased by over 90%. Fecal coliforms also decreased by 92% between the influent and effluent, but the change was not significant. However, NO_x increased from the influent to the effluent as a result of the bacterial nitrification of NH_3 to NO_x. Through denitrification, the DWTU converted most of the NO_x to inert N_2 gas, which is evidenced by the effluent NO_x averaging 8.91 mg/L, a value lower than the USEPA standard for drinking water (10 mg/L). The overall removal of TN by the DWTU averaged 88%, much greater than the 10% removal by conventional septic tanks through accumulation of sludge at the bottom of the tank (Bicki *et al.* 1984). This TN removal is impressive considering that the average influent TN of the DWTU was 118 mg/L, a very high value well above the reported range for TN in raw wastewater effluent (Bicki *et al.* 1984).

Compared to TN, TP removal by the DWTU was relatively low, averaging 38%. The TP concentration of conventional septic tank effluent ranges 11–31 mg/L with a median of 16 mg/L (Bicki *et al.* 1984). In this study, the TP of the DWTU effluent averaged 12.1 mg/L, indicating that the DWTU still performed 25% better than a conventional septic tank. This difference in TN versus TP removal is reflected in the decrease in TN:TP between the DWTU influent (14.2) and effluent (2.32). However, additional TP removal should occur via percolation through the soils of the absorption bed. Although wastewater TN comprised of NO_x is highly mobile in soils and groundwater, this is not the case for TP. A significant amount of TP can be retained or immobilized in soil systems by the mechanisms of adsorption, chemisorption, precipitation, and biological uptake (Bicki *et al.* 1984).

The downgradient groundwater monitoring well, which was less than 10′ (~3.1 m) from the absorption field, allowed for assessment of environmental impacts of the DWTU and showed a decreased amount of reactive N entering the groundwater once the unit was fully operational. This is evidenced by below detection concentrations of NH_3. The maximum groundwater NH_3 concentration observed in this study during the fully operational phase (0.035 mg/L) is in stark contrast to the higher concentrations of groundwater NH_3 that have been observed in other parts of Florida near septic systems, including the Florida Keys (up to 38.5 mg/L) (Lapointe *et al.* 1990), Jupiter (up to 17.9 mg/L) (Lapointe & Krupa 1995), Martin County (up to 50 mg/L) (Lapointe *et al.* 2017), and North Fort Myers (up to 15.3 mg/L) (Brewton *et al.* 2022). The decreased NH_3 loading has significant environmental implications as many HABs preferentially uptake these forms of N (Glibert *et al.* 2016; Kramer *et al.* 2018; Hampel *et al.* 2019).

Groundwater NO_x concentrations also decreased when the DWTU was fully operational. By the last sampling date of the fully operational phase (June 30, 2021), which averaged 12.2 mg/L, groundwater NO_x concentrations were 5.9 mg/L. Similar to NH_3, high groundwater NO_x concentrations downgradient of septic systems have been observed in other locations in Florida, such as in Tampa (up to 56 mg/L) (Bicki *et al.* 1984), the Florida Keys (up to 38.5 mg/L) (Lapointe *et al.* 1990), and Jupiter (up to 21.5 mg/L) (Lapointe & Krupa 1995). While the DWTU in this study generally performed better at TP removal than what has been observed downgradient from septic systems, to meet regulatory requirements and attain levels that are protective of the environmental and human health, some improvement could be achieved through additional chemical filters or advanced performance absorption beds (e.g., using 'Bold & Gold'). However, given the very close location of the monitoring well to the absorption field (~5–10′ or ~1.5–3 m), there was likely very little dilution or adsorption of the DWTU effluent by groundwater before reaching the monitoring well. The slight increase in TP concentrations observed between the effluent and the groundwater monitoring well may be a result of the effluent pooling and concentrating.

Reductions in groundwater TN concentrations were also evident when the DWTU was fully operational. Importantly, groundwater TN concentrations achieved the Monroe County Onsite Wastewater Nutrient Reduction System (OWNRS) goal of $<$10 mg/L by the last sampling date of the fully operational phase (7.0 mg/L). Unfortunately, after this, the residence was vacated, so it was not possible to assess the continued performance of the fully operational system. Influent TN concentrations at this study site were unusually high (118 mg/L), so the ability of the DWTU to minimize groundwater effects at these levels was particularly impressive. A longer study period with the residence occupied and the DWTU fully operational would provide greater insight into the longer-term effectiveness and TN removal capacity.

During this study, the test residence was vacated for approximately six weeks after the DWTU had been fully operational for over three months, which provided an opportunity to assess the performance during a period with no inputs. Once the residence was reoccupied and the treatment process restarted, we observed similar efficiency in removal of nutrients. This suggests the OnSyte DWTU will remain functional during use if the residents of the home are away for an extended period of time. More testing could be done to assess longer durations of non-use to replicate what would occur in DWTUs installed in seasonally occupied residences (e.g., 'Florida snowbirds').

This study provided an initial assessment of the OnSyte DWTU's *in situ* performance but was not comprehensive. Future research should have more replication and examine multiple units operating separately or as part of a system. Additionally, studies could be conducted in varied soil and water table conditions. For example, in Florida it would be important to understand how the DWTU functions in locations with seasonal high water tables, particularly as coastal communities work to mitigate the impacts of climate change and sea level rise. Similarly, it would be useful to assess the impacts of seasonal rainfall on the performance of the DWTU. Finally, longer-term studies to assess the continued performance of a DWTU at both occupied and seasonally occupied homes would also be useful.

5. CONCLUSION

Though some issues were not resolved in this study, such as the limited TP removal capacity, the performance of the OnSyte DWTU for TN removal suggests that this technology offers an alternative method to septic to sewer conversions for improving water quality in areas with conventional septic systems. In-line chemical filters or upgraded absorption fields that can help further denitrify NO_x and provide additional removal capacity for TP could further improve the overall DWTU performance. Florida has a multitude of sensitive aquatic habitats, such as coral reefs, estuaries, and spring systems, and DWTUs may provide the technology to protect these areas from excessive nutrient and bacterial pollution. The OnSyte DWTU may offer a cost-effective alternative to the expansion of underground municipal sewage collection systems, which account for ~ 80% of the capital costs of municipal wastewater collection and treatment systems. This is especially timely for municipalities currently examining options for expanding wastewater infrastructure.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

J. Littlejohn is employed by OnSyte Performance, LLC.

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