Fecal coliform concentrations in effluent from ultraviolet disinfection units installed in onsite wastewater treatment systems

Meagan R. Jackson, John Scott Meschke, Jeremy Simmons and Tania Busch Isaksen

ABSTRACT

Ultraviolet disinfection (UVD) units enhance onsite sewage systems (OSSs) in areas where conventional treatment is limited by site characteristics. Although UVD units are efficacious under testing conditions, few studies have considered their effectiveness when installed. This study used a mixed-methods approach to examine UVD unit effluent quality and determine the association between UV bulb status and fecal coliform levels. Samples from UVD units and pump chambers were tested for bacterial and physiochemical parameters. Field data were supplemented with data from retrospective compliance samples. A multivariate Tobit regression model predicted that the geometric mean (GM) fecal coliform concentration was 122% higher when the UV bulb was deficient than when it was not deficient, adjusted for other OSS deficiencies (95% CI: 36–428, *p*-value <0.001). The predicted GM fecal coliform concentration in malfunctioning UVD unit effluent (745 CFU/100 mL) exceeded field compliance standards (400 CFU/100 mL), and the odds of exceedance were 7.48 times higher when the UV bulb was deficient, adjusted for other OSS deficiencies (95% CI: 4.03–13.9, *p*-value <0.001). Despite limitations in the characterization of UV dose, the results validate the importance of UVD units to reduce bacterial loads and the need for further research into their field effectiveness.

Key words | advanced treatment, fecal coliform, onsite sewage systems, septic systems, ultraviolet disinfection, wastewater treatment

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INTRODUCTION

Onsite wastewater treatment to protect public health

In regions where sewers are not installed, onsite sewage systems (OSSs) treat wastewater and, when operating properly, protect public health by preventing exposure to enteric pathogens. However, OSS discharges and system malfunctions have often resulted in environmental contamination. Especially in densely populated areas, groundwater contamination with untreated wastewater can cause drinking water-associated outbreaks with serious health outcomes (Fong *et al.* 2007; Schneeberger *et al.* 2015). OSSs are also a known source of coastal water contamination, especially when they are improperly installed with inadequate soil treatment (Lipp *et al.* 2001). In regions with large shellfish industries, coastal pollution can result in shellfish contamination and lead to foodborne outbreaks and economic deficits (Geary & Davies 2003). To avoid these outcomes, it is important to ensure that OSSs are properly treating wastewater.

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With increasing population growth and urban sprawl, residential development is expanding to areas where conventional OSSs (composed of a septic tank and soil absorption system) cannot adequately treat wastewater. When soil quality is poor, groundwater tables are high, or OSSs are located close to surface water, advanced OSSs are necessary to provide additional treatment before effluent is discharged into the soil.

Ultraviolet disinfection units

Ultraviolet (UV) disinfection is a long-established technology for drinking water and wastewater treatment (Tchobanoglous *et al.* 2014). When ultraviolet light irradiates pathogens, it inactivates them by damaging nucleic acids. Pyrimidine dimers and other complexes are formed, which prevent replication of genetic material and eventually lead to cell death (Harm 1980). When required doses are met, UV disinfection can inactivate most viruses, bacteria, and protozoan cysts (Hijnen *et al.* 2006).

Achieving adequate UV doses in UVD units depends on the complex interaction of OSS components and wastewater generation. UV dose is determined by the contact time of the wastewater with the UV lamp, the intensity of UV radiation, and the wastewater's UV transmittance. The OSS's hydraulic loading influences the rate of wastewater flow and residence time in the UVD unit, which is also limited by the diameter of the unit. UV intensity decreases with bulb use, so most UVD unit manufacturers recommend replacing UV bulbs at least every two years (Norweco 2014; Salcor Inc. 2016). The organic loading and performance of pretreatment systems also influence UV dose, as they impact the level of suspended and dissolved solids. High solids content decreases UV transmittance because particles, dissolved salts, and organic compounds in the wastewater interact with UV light (Whitby & Palmateer 1993).

UVD unit effluent quality

When UVD units are performing optimally, the UV doses are theoretically sufficient to reduce microbial loads. Under testing conditions, OSSs with UVD units produce effluent with 30-day geometric mean (GM) fecal coliform concentrations below 200 CFU/100 mL (Washington State Department of Health (WADOH) 2012), but few studies have evaluated UVD unit effectiveness in the field. Those that have been performed found that UVD units achieve 2.5-log to 5.7-log fecal coliform reduction under field or simulation conditions, with effluent fecal coliform levels ranging from 1 colony forming unit (CFU)/100 mL to more than 750 CFU/100 mL (Loomis *et al.* 2004; Leverenz *et al.* 2006). Some studies observed biofilms growing on UV bulbs within two months, or sometimes at faster rates when the unit influent contained high solids (Weaver & Richter 2003; Leverenz *et al.* 2006). The biofilms decreased disinfection, but one UVD unit with biofilm buildup was still capable of a 3-log fecal coliform reduction (Leverenz *et al.* 2006). These studies indicate that UVD units can achieve high fecal coliform reductions, but that bacterial disinfection is reduced when the unit is not properly functioning.

Washington State treatment standards for OSSs with UVD units

The Washington State Administrative Code (WAC) requires that registered UVD units be tested with their pretreatment sequences according to National Sanitation Foundation/American National Standards Institute (NSF/ANSI) Standard 40 with bacteriological reduction testing (WADOH 2012). UVD units with pretreatment sequences can be installed to meet Treatment Levels A and B, which require 30-day GM fecal coliform concentrations below 200 and 1,000 CFU/100 mL, respectively, under testing conditions (WAC 246-272A, Table III).

In addition to the standards used for testing purposes, some counties have developed fecal coliform action levels to evaluate OSS performance in the field. The Thurston County action levels are two times the corresponding treatment level standard (e.g., 400 CFU/100 mL for Treatment Level A), and when two or more of the past four effluent samples exceed this level, necessary repairs must be made to improve UVD unit performance (Thurston County Public Health and Social Services (TCPHSS) 2008). These requirements are intended to ensure that OSSs meet expected performance standards, but the general effectiveness of UVD units in the field is not known. Although previous studies have documented effective wastewater treatment in individual OSSs with UVD units, field-based UVD unit effluent has not been well-characterized. This study aimed to describe the effectiveness of a large number of UVD units under field conditions by measuring final effluent quality and determining bacterial reduction due to UVD treatment.

METHODS

Selection of sampling sites

The region for this study was two counties in Washington, USA, which have a total of 2,177 installed UVD units. All owners of UVD units in this region were sent an invitation, which offered a reimbursement of their next required maintenance fee (60–130 USD) in return for participating in the study. The volunteers were primarily from one county, so participants from this county were randomly selected by assigning random numbers to the volunteers and selecting the lowest 65 numbers. Additional participants from the second county were recruited by calling all owners whose phone numbers were recorded in county records. The final sample included 97 UVD units. All studied units were assigned a random ID to ensure confidentiality of participants' results.

Field sampling and measurements

Each studied UVD unit was visited once during a three-month period between June and August, and the UV bulb status at that time was noted. Grab samples were collected from pump chambers and, when sampling ports were accessible, freefalling UVD unit effluent. Samples were collected under the site's conditions upon arrival, between 7:00 and 14:00. When no wastewater was flowing through the OSS, flow was induced by increasing water use in the residence or supplying water into the primary septic tank to simulate natural conditions of higher flow into the OSS. Researchers followed standards of procedure to ensure that collection was consistent and samples were not contaminated. When post-UVD unit sampling ports were accessible, the UVD unit was also turned off, the unit was flushed, and a sample of non-disinfected effluent was collected to determine the treatment level without UV disinfection. Samples were stored at 4 °C and analyzed within 8 hours using the Thermotolerant (Fecal) Coliform Membrane Filter Procedure (Standard Method 9222 D; Francy & Darner 2012). For quality control, the laboratory used *Escherichia coli* as a positive control and *Enterobacter aerogenes* as a negative control and ran daily duplicate samples.

Additional samples were analyzed onsite using direct-reading instruments. The measured wastewater parameters included temperature, pH, dissolved oxygen, conductivity, turbidity, and ultraviolet transmittance (at 254 nanometers), which were measured within 30 minutes of sample collection. The flowrate through the UVD unit was determined by measuring the time needed to fill a 100-mL bottle with freefalling effluent.

Extraction of retrospective quarterly results from inspection reports

In parts of Washington, OSSs with UVD units must be inspected semiannually with quarterly effluent sampling (BH Consulting LLC 2016). Inspection reports from County A are collected through an online data management system. Using Python code, the inspection reports and sampling results were extracted for all UVD unit inspections between 2010 and 2017 for a total of 126 units. OSSs were then classified based on inspection reports as not deficient, deficient in UVD unit, and/or deficient in other OSS components. A UVD unit was classified as deficient if the UV bulb was off or if wastewater was bypassing the unit. Other OSS deficiencies included aerator malfunction, overdue pumping, and power disconnection. The classification from the most recent OSS inspection was attributed to each sampling event; however, if the most recent OSS inspection occurred more than 30 days before the sample collection, no deficiency information was attributed to that sampling event ($n = 13$). When multiple samples were collected between two inspections, the deficiency information was only attributed to the samples when both the preceding and succeeding inspection had identical deficiencies. Inspection records were also used to determine the date of the most recent UV bulb replacement. After data coding, the accuracy was reviewed by comparing 10% of the final classifications to the original extracted database.

Data analysis

The primary goal of data analysis was to describe UVD unit effluent quality in OSSs installed in the field and to determine whether UV bulb status impacts effluent quality. Data analysis was conducted in *R Studio* (version 1.1.414) and *Oracle Crystal Ball*.

Descriptive statistics were calculated for field-collected data and fecal coliform results from regulatory sampling. Because high variability was expected from wastewater samples collected under differing site conditions, no outliers were removed from data analysis. According to the National Shellfish Sanitation Program protocol, fecal coliform results that exceeded the upper limit of detection (LOD) were assigned a value of one CFU above the limit, and results that were below the lower LOD were assigned a value of one CFU below the limit (United States Food and Drug Administration (FDA) 2015). If the LOD was one and there were no colonies detected, the result was recorded as one. Fecal coliform results were $\log_{10}$-transformed for all analyses unless otherwise noted.

To evaluate fecal coliform reduction during UV disinfection, a Wilcoxon rank sum test was used to compare the distribution of fecal coliform levels in samples collected with and without UV disinfection. The fecal coliform log-reduction was calculated by subtracting post-UV fecal coliform concentrations from their paired measurements without UV disinfection.

For freefall effluent samples with UV treatment, the correlation between physical wastewater quality measurements and fecal coliform levels was assessed using a Spearman's rank correlation. The results were compared to scatterplots and Kendall's tau-B correlation coefficients, and each of these analyses yielded similar results.

Because of the large proportion of non-detects in the pump chamber samples, the distributions of pump chamber results divided by UV bulb status were compared visually and using predictive distributions in *Crystal Ball*. The fecal coliform levels in OSSs with a malfunctioning bulb were compared to the percentiles of a custom distribution of fecal coliform concentrations created with the data from properly functioning bulbs.

The association between UV bulb status and fecal coliform levels in retrospective compliance data was assessed using a multivariate Tobit regression model (see Equation (1)). Fecal coliform results were $\log_{10}$-transformed after adjusting for non-detects in the data (adding one to each value). Because Tobit regression models usually assume normal distribution of the outcome variable, the accuracy of the model was confirmed by conducting a rank normal transformation of the outcome variable and running the same model, which yielded similar results. A subgroup analysis of the effect of ln-transformed bulb age on fecal coliform concentrations was performed for observations where the UV bulb was on.

$$Y_i^* = \beta_0 + \beta_1^* X_i + \varepsilon_i, \tag{1}$$

where: $Y_{ij}^* :=$ log-fecal coliform for observation i at site j; $X_{ij} :=$ covariates for observation i at site j (include *UV deficiency* and *other deficiency*, with *age* added for subgroup analysis); and $\varepsilon_{ij} \sim N(0, \Sigma) :=$ error term clustered at the OSS level to account for inter-OSS interdependence.

The model predicted Y_i^*, the latent variable underlying the observed fecal coliform concentrations, which are:

$$Y_i = \begin{cases} LOD_{U_i}, & Y_i^* \geq LOD_{U_i} \\ LOD_{L_i}, & Y_i^* \leq LOD_{L_i} \\ Y_i^*, & otherwise \end{cases}$$

Additionally, the impact of UV bulb deficiency on the likelihood of exceeding the OSS's action level, adjusted by the presence of other OSS deficiencies, was examined using a multivariate logistic regression model (see Equation (2)). Censored results that could not be classified as to action level exceedance were removed from the model ($n = 152$).

$$\text{logit}(FC\ exceeding\ AL_i) = \beta_0 + \beta_1 * \text{UV deficiency}_\text{i} + \beta_2 * \text{other deficiency}_\text{i} \tag{2}$$

RESULTS

UVD units observed in the field

Researchers inspected 97 UVD units, which included units from three different manufacturers. Inspected units were preceded by aerobic treatment units from various manufacturers or intermittent sand filters. Important characteristics

Table 1 | Performance specifications for two UVD unit models

	Product A[a]	Product B[b]
Lamp type	Low-pressure mercury, 90% output at 253.7 nanometers	Low-pressure mercury, 90% output at 253.7 nanometers
Nominal UV intensity at 1 meter (microW/cm^2)	Greater than 190	112
Minimum UV dose, under optimal conditions (mJ/cm)	55	Information not available
Approximate UVD unit volume (L)[c]	3.2	2.9
Irradiation time with 10 mL/s flowrate (min)	5.3	4.8

[a] Salcor Inc. (2011). (Note that these specifications are for the second version of the Salcor 3G UV Disinfection Unit. Some observed Salcor 3G units were the first model version, for which specifications are not available.)

[b] Hydro Action (n.d.).

[c] Calculated from manufacturer specifications and drawings.

of UVD units are included in Table 1. Because Washington State regulations expect all approved treatment trains to achieve predetermined standards of advanced wastewater treatment, study results were not grouped by treatment sequence for analysis.

Wastewater quality of UVD unit effluent from field sampling

Freefall effluent samples were collected from 22 OSSs with UVD units, which did not have any indicators of significant malfunctions. Table 2 shows descriptive statistics for all freefall samples, as none were considered outliers.

Fecal coliform levels were measured with the UV bulb turned off in 17 UVD units. The GM fecal coliform concentration without UV disinfection was 2.8×10^3 CFU/100 mL (geometric standard deviation (GSD) = 7.6, range = 40–1.2×10^5 CFU/100 mL). Based on a Wilcoxon rank sum test, there was a statistically significant difference between the distribution of fecal coliform concentrations with and without UV disinfection ($p < 0.001$). The mean $\log_{10}$-reduction in the UVD unit was 2.1 (SD = 1.0, range = 0.6–3.6). In other words, the UVD units on average successfully removed 99% of the fecal coliforms present in the influent wastewater.

Post-UV fecal coliform concentrations had a strong positive correlation with conductivity. Fecal coliform was also positively correlated with turbidity and flowrate and negatively correlated with UV transmittance, although the correlations with flowrate and UV transmittance were not statistically significant (see Table 1).

Wastewater quality in pump chambers following UVD units

The GM fecal coliform concentration (95 ± 20 CFU/100 mL; minimum: below limit of detection, 10 CFU/100 mL; maximum: above LOD, 2×10^6 CFU/100 mL) was higher for pump chamber samples than for freefall effluent samples. The descriptive statistics for pump chamber fecal coliform concentrations grouped by UV bulb status are given in Table 3 (see Supplementary Table S1 for the characteristics of OSSs where pump chamber samples were collected, available with the online version of this paper). Among OSSs with malfunctioning UV bulbs, three of the five pump chamber fecal coliform measurements that exceeded the lower LOD also exceeded the 75th percentile of the measurements from OSSs with properly functioning UV bulbs, which was 225 CFU/100 mL (see Figure 1). However, due to the small sample size and high variability, the association between UV bulb status and pump chamber fecal coliform concentrations could not be determined.

Wastewater quality in retrospective quarterly compliance samples

Quarterly sampling reports from 2010 to 2017 included 2,711 records of fecal coliform measurements from 126 different OSSs, of which the average operation time had been 12.5 years (SD = 5.9, min = 1, max = 31). Of all the fecal coliform measurements, 2,377 (88%) were taken when the UV bulb was not deficient, 65 (2%) when the UV bulb was deficient, and for 269 (10%) of the samples,

Table 2 | Wastewater quality of freefall UVD unit effluent and correlation with log-fecal coliform (FC) (n = 22)

	Mean ± SD[a] (min–max)	**Spearman's rho correlation with log-FC**	***p*-value**
Fecal coliform (CFU/100 mL)[b]	18.1 ± 3.6 (<10–690)	–	–
Temperature [°C]	21.1 ± 2.5 (16.7–25.6)	0.11	0.639
pH	6.7 ± 0.8 (4.8–8.3)	−0.08	0.715
Dissolved oxygen [mg/L]	6.8 ± 2.0 (5.4–8.3)	−0.01	0.964
Conductivity [μS/cm^2]	612 ± 302 (227–1,308)	0.67	**<0.001**
Turbidity [NTU][c]	20.4 ± 19.6 (0–60.6)	0.49	**0.032**
UV transmittance [%]	44.5 ± 17.7 (13.3–74.0)	−0.40	0.063
Flowrate [mL/s]	10.2 ± 9.7 (0.5–37.5)	0.41	0.063
Residence time in UVD unit [min][d]	18 ± 30 (1.3–116)		
OSS age [years]	11.6 ± 5.5 (1–22)		
Months since last inspection	4.1 ± 4.3 (0.5–19)		
Months since last bulb replacement	27.8 ± 17.0 (2.0–67.6)		
Months since last cleaning	4.8 ± 5.6 (0.5–20.8)		
UVD unit make[e]			
Salcor 3G	27%		
The Disinfector	73%		
ATU Make[e]			
BioMicrobics	73%		
Delta Environmental	14%		
Other	14%		

[a] SD: standard deviation.

[b] Reported statistics are GM ± GSD.

[c] Due to instrument imprecision, turbidity measurements should be considered estimated values (within 10 NTU of the true value). It is unlikely that turbidity values are significantly biased.

[d] Approximate values calculated from flowrate measurements and unit volume estimates.

[e] Values are percentages of all observed UVD units represented by the given UVD unit make or ATU make that precedes UVD units in treatment sequence.

Table 3 | Fecal coliform concentrations in pump chambers following UVD units (in CFU/100 mL)

	N	***n* > LOD[a]**	**Mean**	**SD**	**GM**	**GSD**	**Min**	**25th %**	**Mdn**	**75th %**	**Max**
Working	37	23	2,875	10,322	68	13	<10	<10	<10	225	56,000
Not working[b]	10	5	15,878	47,177	75	40	<10	<10	<10	1,295	150,000
NA[c]	6	5	36,106	80,504	1,073	13	<10	194	745	11,532	>200,000
All	**53**	**30**	**9,091**	**34,680**	**95**	**20**	**<10**	**<10**	**20**	**541**	**>200,000**

[a] Number of samples with fecal coliform concentrations greater than the LOD (10 CFU/100 mL for most samples).

[b] UV bulbs classified as not working if UV bulb was off or had high biofilm deposit. Of the observed UVD units, six UV bulbs were off, three UV bulbs were both off and covered with a high biofilm deposit, and one was on with a high biofilm deposit.

[c] UV bulb status could not be determined.

the UV bulb status could not be determined. The GM fecal coliform concentration when the UV bulb was functioning was 26.3 CFU/100 mL (GSD = 7.3, <1–8.0 × 10^4 CFU/100 mL) and 297.3 CFU/100 mL when the UV bulb was deficient (GSD = 10.6, <1–5.9 × 10^4 CFU/100 mL; see Figure 2). Estimates from the multivariate Tobit regression model show a significant association between fecal coliform concentrations and UV bulb deficiency (see Table 4). On average, the GM fecal coliform concentration was 122% higher in OSSs with deficient UV bulbs than in OSSs with functioning UV bulbs, after adjusting for other OSS deficiencies (*p*-value <0.001). The 95% confidence interval

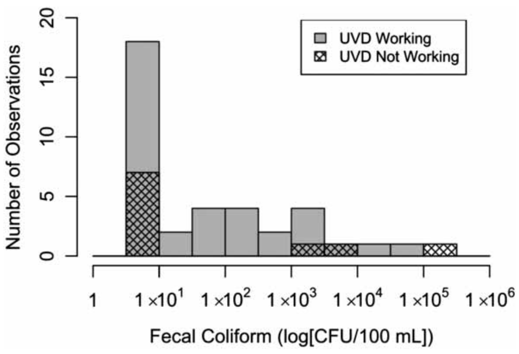

Figure 1 | Distribution of fecal coliform concentrations in pump chambers, divided by OSSs with and without working UVD units.

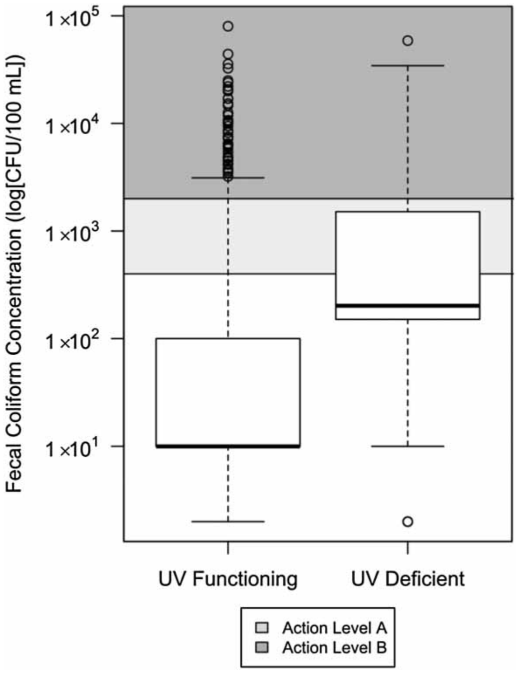

Figure 2 | Fecal coliform concentrations in OSSs with UV disinfection units, divided by presence of UVD deficiency and compared to regulatory action levels (Action Level A = 400 CFU/100 mL, Action Level B = 2,000 CFU/100 mL).

(CI) for the GM, calculated with no measurements considered outliers, was 36–428. The predicted GM fecal coliform concentration in effluent from OSSs with a deficient UV bulb, but without other OSS deficiencies, was 745 CFU/100 mL, and in effluent from OSSs without any deficiencies, the predicted GM fecal coliform concentration was 6.1 CFU/100 mL. A subgroup analysis showed that there was no significant association between bulb age and fecal coliform concentrations when the UV bulb was on (GM ratio = 1.33, 95% CI = 0.66–2.67, *p*-value = 0.429).

Among the fecal coliform results from quarterly compliance samples, 197 (7.7%) excceded the action level for the OSS from which they were sampled. The exceedance could not be determined in 152 (5.6%) of the samples due to censored data. The proportion of samples exceeding the action level was higher when the UV bulb was deficient (36.2%) than when the UV bulb was properly functioning (6.8%). Table 5 depicts the exceedance prevalence stratified by UV bulb status and OSS action level.

Logistic regression analysis indicated that among OSSs that have the same status of other deficiencies (excluding UVD unit deficiency), the odds of effluent fecal coliform levels exceeding the action level were 7.48 times higher when the UV bulb was deficient than when the UV bulb

Table 5 | Proportion of OSSs exceeding action level (in %)

Action level	UV bulb not deficient	UV bulb deficient	All
A/1 (400 CFU/100 mL)	9.2	45.5	10.4
2 (1,600 CFU/100 mL)	4.6	27.6	5.3
B (2,000 CFU/100 mL)	5.6	42.9	6.6
All	6.8	36.2	7.4

Table 4 | Multivariate Tobit regression model estimates for GM fecal coliform concentrations

	Raw model			Exponentiated model		
	Estimate	Standard error	95% CI[a]	Estimate	95% CI	*p*-value
Intercept	0.782	0.101	0.58–0.98	6.05	3.84–9.55	
UV deficiency[b]	2.09	0.276	1.55–2.63	123	35.5–428	<0.001
Other deficiency[c]	0.172	0.187	−0.20–0.54	1.48	0.64–3.46	0.359

[a] 95% confidence interval.

[b] UV bulb off or OSS flow bypassing the UVD unit.

[c] Deficiency in OSS component other than UVD unit. Includes aerator malfunction, overdue pumping, and lack of electrical power to the OSS.

Table 6 | Multivariate logistic regression model estimates for exceedance of fecal coliform action levels

	Raw model		Exponentiated model		
	Estimate	Standard error	Estimate	95% CI[a]	*p*-value
Intercept	−2.65	0.09	0.07	0.06–0.08	
UV deficiency[b]	2.01	0.31	7.48	4.03–13.9	<0.001
Other deficiency[c]	**0.35**	**0.22**	**1.42**	**0.91–2.19**	**0.120**

[a] 95% confidence interval.
[b] UV bulb off or OSS flow bypassing the UVD unit.
[c] UV bulb status could not be determined.

was properly functioning (95% CI: 4.03–13.9, *p*-value <0.001; see Table 6). This model predicts a 0.07 odds (95% CI: 0.06–0.08) or 6.5% (95% CI: 5.7–7.4%) probability of exceeding the action level when there is no deficiency with the UVD unit or other OSS components.

DISCUSSION

Field performance of UVD units

Based on freefall effluent samples collected in the field, when UVD units and their pretreatment sequences are properly functioning, they usually produce effluent with low fecal coliform levels that meet treatment standards. For these samples, the range of final fecal coliform concentrations was similar to those measured from individual OSSs in previous studies; however, the mean log-reduction of 2.1 was lower than the 2.5–5.7 log-reductions previously observed (Loomis *et al.* 2004; Leverenz *et al.* 2006). Because of low flowrates in the inspected OSSs or possible low microbial concentrations in the OSS influent, the pretreatment could have provided sufficient treatment to reduce fecal coliform levels such that the influent to the UVD unit had lower bacterial levels than those observed in previous studies. High biofilm buildups and old bulbs were not noted as significant issues during field inspections, but these could also reduce microbial inactivation.

Although NSF/ANSI Standard 40 treatment levels are given as 30-day geometric means, they are helpful benchmarks to which to compare effluent values to evaluate their risk to human health. All but two of the 22 effluent samples (91%) met the lowest fecal coliform standard for Treatment Level A (200 CFU/100 mL), indicating that these UVD units were providing high-quality effluent.

Effluent samples for bacterial analysis were collected under a wide range of flow conditions that could not be precisely measured, although most flowrates were significantly lower than the average flow through an OSS (see Table 2). The flowrates were either natural or simulated-natural conditions, and the fecal coliform values measured in the effluent are therefore representative of bacterial levels measured from UVD units in the field, where flowrates are highly variable.

Bacterial effluent quality was strongly correlated with conductivity and turbidity, although due to imprecise measurements, turbidity values should be considered estimates of true turbidity. As noted by Leverenz *et al.* (2006), wastewater with high solids content is difficult to disinfect with ultraviolet disinfection. Both septic tanks and aerobic treatment units reduce solids content, although the reduction is generally greater in aerobic treatment units. These can achieve effluent total suspended solids (TSS) values between 17 and 40 mg/L, although higher TSS values have been observed (United States Environmental Protection Agency (US EPA) 2002; Levett *et al.* 2010). The correlation observed between solids content and final effluent fecal coliform levels indicates that the performance of aerobic treatment units may be an important factor in determining the ability of OSSs with UVD units to reduce fecal coliform levels below treatment standards.

Wastewater quality in pump chambers following UVD units

The fecal coliform concentrations measured in pump chambers included much higher values than those in UVD unit effluent samples. Pump chambers both with and without functioning UVD units had maximum fecal coliform concentrations exceeding 5×10^4 CFU/100 mL. This indicates that pump chamber conditions are conducive for bacterial regrowth, and fecal coliform concentrations measured in UVD unit effluent may not represent the quality of the wastewater being discharged from the pump chamber. However, mean pump chamber fecal coliform concentrations observed in this study are lower than fecal coliform concentrations previously measured in pump chamber effluent after ATUs, in which ATUs with fabric filters had a mean fecal coliform concentration of 2.4×10^4 CFU/100 mL, and ATUs without fabric filters had a mean fecal coliform concentration of 1.5×10^5 CFU/100 mL (Converse & Converse 1998). The mean fecal coliform level from pump chambers with UV disinfection (3.0×10^3 CFU/100 mL) is at least 1-log lower than those in pump chambers with only ATU treatment, whereas the mean fecal coliform concentration in pump chambers without UV disinfection (1.6×10^4 CFU/100 mL) is in the same log-range as the mean fecal coliform concentration in ATUs with fabric filters. The lower bacterial concentrations observed in this study may be due to UV disinfection, ATU technology improvements, or other unobserved wastewater properties and OSS characteristics.

Pump chamber samples also had high variability (SD = 3.4×10^4 CFU/100 mL). This corresponds with previous observations that pump chamber samples yield high standard deviations and that surveying wastewater quality in pump chambers is difficult because of the many factors that influence it (Converse & Converse 1998; Hinkle *et al.* 2005). Although the sample size of this study was not large enough to test statistical hypotheses, the pump chamber results do show a trend of higher variability and higher mean fecal coliform values when UV bulbs are malfunctioning. Additional studies should verify this trend by including a larger sample size and controlling for other aspects that influence wastewater in pump chambers. These could include time since the chamber solids were removed, time since the pumped dosing, and the hydraulic and organic load of OSS influent. Additional information about the UV dose applied to the wastewater collected from the pump chamber would also clarify the contribution of the UVD unit to bacterial reduction.

UVD unit effluent quality characterized from regulatory sampling

When considering retrospective compliance samples from OSSs with UVD units, the GM fecal coliform concentration was, on average, 122% higher when the UVD unit was deficient, after adjusting for other OSS deficiencies. This difference is statistically significant ($p < 0.001$) and indicates that the UVD unit does contribute to bacterial reduction. However, the magnitude of the difference in fecal coliform concentrations is relatively small, which could indicate that the UVD unit treatment is lower than expected. Additionally, because of the high variance around the GM fecal coliform values in UVD units with and without deficiencies, there are some cases where the fecal coliform concentration is lower in deficient UVD units than in those that are fully functioning. Important factors that were not considered in this comparison, such as influent organic and hydraulic load, ATU performance, or other aspects of UVD unit performance, including retention time and biofilm buildup, could have contributed to the exceedances and high variability observed in some properly functioning UVD units. Despite the variability in bacterial concentrations, the retrospective samples do show an important contribution of UVD units to minimizing exceedances of treatment standards. Eight percent of the retrospective fecal coliform results exceeded the OSS's action level standard, but this proportion was significantly higher when looking only at UVD units where the UV bulb was deficient (36%).

Although other characteristics of OSS operation and performance contribute to final effluent quality, the large odds ratio for action level exceedance indicates that UVD units contribute substantially to providing well-treated effluent, and it is crucial that they are properly installed and well-maintained so that UV bulbs are properly operating at all times. Additionally, the Tobit regression model predicted a GM fecal coliform concentration for deficient UVD units (745 CFU/100 mL) that exceeded action level A, but not higher action levels. Although multiple measurements from an individual UVD unit are compared to the action level for regulatory purposes, this shows that inadequate treatment is more likely to occur on sites that require higher treatment levels. Proper functioning of UV bulbs is especially important for sites that require Treatment Level A. A tiered maintenance program that prioritizes Treatment Level A OSSs may be a cost-effective approach to increase compliance with fecal coliform effluent standards.

Limitations and suggestions for further research

Only a small number of effluent samples were accessible during this study. Most freefall effluent samples were collected during periods of low flow, which may bias the averaged results to be lower than would be measured with higher flowrates. Additionally, no freefall effluent samples could be collected from units with malfunctioning UV bulbs. These limitations brought to attention the need for more consistent installation of freefall sampling ports after UVD units, which would facilitate more extensive effluent sampling and routine monitoring.

For the purposes of this study, using results from retrospective quarterly sampling compensated for the small sample size. This dataset provided enough measurements to answer the questions of interest, but had limitations of its own. Many of the fecal coliform measurements were right-censored due to a lack of follow-up laboratory analysis on regulatory samples. Additionally, because the dates of OSS repairs were not consistently reported, some deficiencies could have been misclassified when reviewing inspection reports. Data gaps likely resulted in nondifferential misclassification and an attenuation of the true associations. Despite these limitations, significant relationships between UVD unit status and effluent quality were identified. Consistent methods and reporting during OSS inspections, effluent sampling, and repairs could prevent similar limitations in the future.

Beyond UVD unit effluent and pump chamber samples, additional measurements throughout the OSS would better capture the treatment achieved by different components and the specific contribution of the UVD unit. Influent wastewater quality determines the amount of microbial reduction that is required, and if it is especially poor, may also affect final fecal coliform levels. Treatment in the aerobic unit is also important to capture, as the results from this study indicated that aerobic treatment unit performance may be an important determinant of UV transmittance and the ability for UVD units to reduce bacterial load. In addition to determining the level of treatment achieved before UVD units, more insight is needed into the bacterial reduction that takes place in soil absorption systems. Although this is an important consideration, it is difficult to capture due to the variability in soil conditions around OSSs.

The lack of detailed information about the sampled wastewater's retention time in the UVD unit and biofilm buildup on the UV lamp also limits our understanding of how OSS characteristics could have impacted UV dose at the time of sampling. By characterizing the intensity of the UV bulb and the irradiation time, additional insight could be gathered regarding the most important management interventions to improve UVD unit performance.

CONCLUSION

This study provides important insights as the first large-scale analysis of UVD units installed in the field. Its results demonstrate evidence that properly functioning UVD units after pretreatment sequences are capable of reducing bacterial levels and providing high quality effluent, which supports further research into site characteristics that impact performance and effective design, operation, and maintenance of the units. In cases where UV bulbs are malfunctioning, the lack of disinfection results in effluent discharges that may pose risks of water contamination and spread of illness. Public health practitioners and professionals in the onsite wastewater industry should make special efforts to ensure that UVD units are functioning properly and providing disinfection.

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