

Field Effectiveness of Ultraviolet Disinfection in Onsite Wastewater Treatment

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Abstract

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Ultraviolet disinfection (UVD) units provide advanced onsite wastewater treatment, which is essential in regions where soils are unsuitable for conventional onsite sewage systems (OSSs). Although UVD treatment systems provide high-quality effluent under testing conditions, field effectiveness of UVD units is poorly understood. This study aimed to determine the field performance of UVD units installed in Western Washington, their ability to provide high-quality wastewater effluent, and risk factors for UVD unit malfunction. The hypothesis, based on a previous report from Kitsap County, was that 25-50% of UVD units would have malfunctioning UV bulbs and that malfunctioning units would have higher fecal coliform effluent levels than those performing optimally.

This study used a mixed-methods approach with original data collection and complimentary analysis of retrospective quarterly compliance samples. 97 UVD units were inspected for indicators of unit performance, and wastewater samples from 53 units were collected and analyzed for physical wastewater quality, fecal coliform concentrations, and, in 21 units, presence of male-specific (F+) coliphage. Data from inspection and sampling reports provided additional insights into provided maintenance and retrospective UVD unit performance.

The study results indicated that properly functioning and well-maintained UVD units reduce fecal coliform concentrations to low levels, but that 25% of the UVD units in the study area have malfunctioning UV bulbs that are inhibiting disinfection (95% CI: 18-34%). The geometric mean (GM) fecal coliform concentrations of field samples collected after functioning UVD units (GM=18 ± 4 CFU/100 mL) was well-below the lowest Washington State Treatment Level standard (200 CFU/100 mL). Based on a multivariate Tobit regression model of retrospective compliance data, the GM fecal coliform concentration in UVD units with deficient bulbs was 122% higher than in UVD units with bulbs that were not deficient, after adjusting for other OSS deficiencies (95% CI: 36-428%, $p < 0.001$) and the odds of effluent exceeding fecal coliform standards were 7.5 times greater among UVD units with deficient bulbs than among UVD units with glowing bulbs, after adjusting for other OSS deficiencies (95% CI: 4.0-13.9, $p < 0.001$). During field sampling, male-specific coliphages were detected in 24% of 21 post-UV samples, and issues with the UVD unit were identified in all units positive for coliphage. Based on these results, many UVD units in the field are not providing optimal disinfection, and their effluent may pose a risk to public health.

Based on onsite inspections of UVD units, inadequate maintenance (present in 77% of inspected UVD units) and electrical problems (present in 15% of inspected UVD units) are potential risk factors for UV bulb malfunction. Additionally, large discrepancies in county-level prevalence of UV bulb malfunction indicate that local management of operation and maintenance has a significant impact on UVD unit performance. These findings have implications for preventing future failures of UVD units that are already installed, implementing a high-quality maintenance program when initiating the use of UVD units in new regions, and improving the design of innovative onsite treatment systems.

TABLE OF CONTENTS

Abstract	3
List of Appendices	6
List of Tables	7
List of Figures	10
Abbreviations and Acronyms	12
Acknowledgements	14
Literature Review	17
Study Aims	31
Fecal Coliform Concentrations in Effluent from Ultraviolet Disinfection Units Installed in Onsite Wastewater Treatment Systems	33
Operation and Maintenance Factors Impacting Performance of Ultraviolet Disinfection Units in Onsite Sewage Systems	53
Male-Specific Coliphage in Onsite Sewage Systems with UVD units	69
Homeowner Feedback about UVD Units	77
Certified Maintenance Provider Perspective	82
Conclusion	85
Bibliography	86

LIST OF APPENDICES

Appendix A. Methods.....	94
Appendix B. Letter of Invitation to Participate in Study.....	108
Appendix C. UVD Unit Field Inspection Checklist.....	111
Appendix D. Representativeness of Study Sample.....	112
Appendix E. Graphs and Tables to Supplement Data Analysis.....	115
Appendix F. Research Translation Materials.....	134

LIST OF TABLES

Table 1. Proprietary Treatment Products with Ultraviolet Disinfection, Registered for Use in Washington State for Treatment Levels (TL) A–E and Treatment Level	22
Table 2. Treatment Component Performance Testing Standards	24
Table 3. Estimates of Residential Wastewater Quality.....	26
Table 4. Wastewater Quality of Freefall UVD Unit Effluent (n=22).....	42
Table 5. Fecal Coliform Concentrations in Pump Chambers Following UVD Units (in CFU/100 mL).....	44
Table 6. Multivariate Tobit Regression Model Estimates for Geometric Mean Fecal Coliform Concentrations	46
Table 7. Proportion of OSSs Exceeding Action Level (in %)	46
Table 8. Multivariate Logistic Regression Model Estimates for Exceedance of Fecal Coliform Action Levels	47
Table 9. Characteristics of Ultraviolet Disinfection Units and Observed Indicators of Suboptimal Performance	60
Table 10. Time, in Months, since Most Recent Maintenance Performed on UVD Units	62
Table 11. Odds Ratios for UV Bulb Malfunction (UV Bulb Not Glowing).....	63
Table 12. Prevalence of F+ Coliphage in Pump Chamber Samples (n=21).....	74
Table 13. Homeowners’ Access to Contact Information for Key Players in OSS Maintenance and Management.....	78
Table 14. Proportion of Homeowners Interested in Different OSS Topics	78

Table A.1 Physical Wastewater Quality Parameters and Analytical Methods	98
Table A.2 Variables Used as Predictors in L1 Regularized Model	107
Table D.1. Characteristics of Sampled and Studied OSSs in Comparison with All OSSs in Pierce and Thurston Counties	113
Table D.2. P-values of t-tests and chi-squared proportions tests to determine representativeness of studied OSSs.....	114
Table E.1. Descriptive Statistics of Fecal Coliform Concentrations Stratified by UV Bulb Deficiency.....	119
Table E.2 Descriptive Statistics of Fecal Coliform Concentrations Stratified by Presence of Other OSS Deficiency.....	120
Table E.3 Prevalence of Other Deficiencies in OSSs with and without UV Bulb Deficiencies.....	121
Table E.4. Descriptive Statistics of Fecal Coliform Concentrations, Stratified by Age of UV Bulb.....	122
Table E.5. Descriptive Statistics of Age of Bulb in Months, Stratified by UV Bulb Deficiency	123
Table E.6. Tobit Regression Model Estimates for the Association Between Geometric Mean Fecal Coliform Concentrations and UV Bulb Age	124
Table E.7. Multivariate Tobit Regression Model Estimates for Geometric Mean Fecal Coliform Concentrations with Sample Location Included	124
Table E.8. Wastewater Quality of UVD Unit Effluent Compared to Pump Chamber	128
Table E.9. Odds Ratios for UV Bulb Malfunction for Binary Variables, Calculated with Fisher’s Exact Test.....	132

Table E.10. Odds Ratios for UV Bulb Malfunction for Non-Binary Variables, Calculated with
Logistic Regression.....132

Table E.11. Male-specific (F+) Coliphage Concentrations in OSSs with UVD Units.....133

LIST OF FIGURES

Figure 1. Individual and Mean Fecal Coliform Reductions in Ultraviolet Disinfection Units, as Characterized by Sampling UVD Unit Effluent with UVD Unit Turned On and Turned Off	43
Figure 2. Distribution of Fecal Coliform Concentrations in Pump Chambers, Stratified by OSSs With and Without Working UVD Units	44
Figure 3. County-level Differences in Installation and Maintenance-Related Issues of Ultraviolet Disinfection Units	61
Figure 4. Proportion of Septic Owners Who Have Access to Record Drawings and Operation and Maintenance Manuals	77
Figure 5. Frequency of Septic Owners Inspecting Their UVD Unit	79
Figure E.1. Histogram of Non-transformed and log-Transformed Fecal Coliform Concentrations in Samples from Post-UVD Unit, Post-UVD Unit Without Disinfection, and Pump Chamber	115
Figure E.2. Histogram of log-Transformed Fecal Coliform Concentrations from Retrospective Quarterly Compliance Samples	116
Figure E.3. Scatterplots of Correlations between Physical Wastewater Quality Parameters and log-Transformed Fecal Coliform Concentrations	117
Figure E.4. Boxplot of log-Transformed Fecal Coliform Concentrations Stratified by Presence of Deficiency in OSS Component Other than the UVD Unit	120
Figure E.5. Distributions of Non-transformed and log ₁₀ -Transformed Age of UV Bulbs at Time of Quarterly Compliance Sampling	121

Figure E.6. Associations Between Fecal Coliform Concentration and UV Bulb Age, with Lowess Lines Indicating Difference in Association Depending on UV Bulb Deficiency.....	122
Figure E.7. Fecal Coliform Concentrations in Retrospective Compliance Samples with Known Sampling Location, Stratified by Sampling Location (UVD Unit Freefall and Pump Chamber).....	125
Figure E.8. Synthetic Beta-Poisson Distribution Generated from the Detected Fecal Coliform Concentrations in Pump Chambers of OSSs with Functioning UVD Units.....	126
Figure E.9. Proportion of UVD Units with UV Bulb Off Stratified by Indicators of Suboptimal Installation, UVD Unit Characteristics, and UVD Unit Performance as Predictors	129
Figure E.10. Differences in UVD Unit Installation and Maintenance Characteristics Stratified by UV Bulb Status	131

ABBREVIATIONS AND ACRONYMS

BOD₅: 5-day biochemical oxygen demand

CBOD₅: 5-day carbonaceous biochemical oxygen demand

CFU: Colony forming unit

CI: Confidence interval

cm: Centimeter

FC: Fecal coliform

F+ coliphage: Male-specific (or F-specific) coliphage

GM: Geometric mean

GSD: Geometric standard deviation

LOD: Limit of detection

max: maximum

min: minimum

MPN: most probable number

NSF/ANSI: National Sanitation Foundation/ American National Standards Institute

NSSP: National Shellfish Sanitation Program

OSS: Onsite sewage systems

SAL: Single agar layer

SAS: Soil absorption system

SD: Standard deviation

TCPHSS: Thurston County Public Health and Social Services

TPCHD: Tacoma-Pierce County Health Department

TSS: Total suspended solids

US EPA: United States Environmental Protection Agency

UV: Ultraviolet

UVD: Ultraviolet disinfection

UVT: Ultraviolet transmittance

WAC: Washington State Administrative Code

WADOH: Washington State Department of Health

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LITERATURE REVIEW

Advanced Onsite Wastewater Treatment

Onsite wastewater treatment is an essential component of environmental health services and interventions to protect public health. In rural and suburban areas without sewers, onsite treatment is necessary to reduce public contact with the pathogens present in wastewater and to protect environmental quality. Approximately one third of houses in the United States have onsite wastewater treatment systems, and 30% of new construction depends on onsite sewage systems (OSSs; Thompson, 2018; United States Environmental Protection Agency [US EPA], 2002). Although onsite treatment is widespread, approximately two thirds of U.S. land is unsuitable for conventional onsite sewage systems, so OSSs in these locations require additional treatment before effluent is discharged into natural environments (US EPA, 2002). Because conventional systems depend on soil to reduce microbial levels, OSSs on sites with medium- to coarse-grained soils, reduced vertical setbacks to groundwater (high water tables), or reduced horizontal setbacks to surface waters must provide additional treatment before effluent is discharged (Washington State Department of Health [WADOH], 2017). Examples of advanced treatment systems include intermittent sand filters, aerobic treatment units, and disinfection (US EPA, 2002). As populations grow and urban sprawl causes residential areas to spread, the need for advanced onsite wastewater treatment is likely to increase.

Onsite Wastewater Treatment for Public Health Protection

In 2005, the US Environmental Protection Agency (US EPA) estimated that approximately 20-30% of OSSs in the U.S. were failing (US EPA Office of Water, 2005). Although many environmental health departments have actively identified and repaired failing systems since then, many still pose a threat to environmental and public health. Especially when

OSSs are located in sensitive areas, wastewater can contaminate ground and surface water, and the enteric bacteria, viruses, and protozoan cysts present in residential wastewater can lead to health problems (US EPA, 2015).

For example, insufficient onsite wastewater treatment can cause groundwater contamination (Carroll, Goonetilleke, & Hargreaves, 2004; Miller & Ortiz, 2001; Schneeberger et al., 2015). Especially in densely populated areas where properties are small, private wells are at risk of pumping OSS leachate that contains fecal bacteria and nitrates (Bremer & Harter, 2012; S. Carroll et al., 2006), which can lead to drinking water outbreaks (Fong & Lipp, 2005).

OSS effluent has also contaminated coastal waters, especially when the systems are improperly installed without adequate soil treatment (Duda & Cromartie, 1982; Lipp, Farrahà, & Rose, 2001). It is important to note that even when fecal coliforms contaminate groundwater, they can be attenuated before reaching shorelines, so the distance to surface water is an important determinant of coastal pollution (Reay, 2004). When wastewater does pollute coastal waters, shellfish contamination can have detrimental effects through foodborne outbreaks. OSS discharges have reduced the water quality at many shorelines important for the shellfish industry in Puget Sound and throughout the world, with negative impacts on the shellfish economy as well as the indigenous communities for whom shellfish collection is an important cultural heritage (Alastair, James, Michelle, & Ron, 2009; Geary & Davies, 2003; WADOH, 2016). Because insufficient wastewater treatment can cause significant economic damage and severe health problems, it is essential to ensure that advanced treatment systems are properly functioning.

Ultraviolet Disinfection for Advanced Treatment

Ultraviolet (UV) disinfection is one form of advanced treatment that has been applied for drinking water, municipal wastewater, and onsite wastewater. It is often the only component of a treatment sequence that is designed specifically to inactivate microorganisms. Wastewater treatment designers have especially been interested in UV disinfection for situations where effluent must meet strict quality standards, for example for surface water discharge, direct reuse of wastewater, or where soil absorption systems (SASs) have limited depth or soil quality (US EPA, 2002).

UV irradiation inactivates pathogens by damaging nucleic acids, which are essential for replication and survival. DNA and RNA absorb radiation between 190 nm and 380 nm, with a peak at 253.7 nm (Harm, 1980). Most often, photoactivation causes adjacent pyrimidines to form dimers; strand breaks and interstrand crosslinks can also occur, but are very rare (Harm, 1980; Rastogi, Richa, Kumar, Tyagi, & Sinha, 2010).

The amount of pathogen inactivation is determined by UV dose, which is a product of contact time, UV intensity, and UV transmittance. In onsite wastewater treatment, contact time is a result of wastewater generation in the household and the hydraulic load to the OSS. UV intensity should be between 35,000 and 70,000 mW-s/cm² to achieve the required bacterial reduction for wastewater (US EPA, 2002). Because the intensity of UV bulbs wanes over time, regular bulb replacement is necessary to maintain adequate intensities. UV transmittance is a characteristic of a fluid and is defined as the proportion of UV light that travels through 1 cm of the fluid compared to deionized water. In wastewater disinfection, UV transmittance is an especially important component of UV dose because the suspended particles and dissolved organic compounds in wastewater can absorb, reflect, refract, or scatter light, decreasing the amount of UV radiation that contacts microorganisms (Hijnen, Beerendonk, & Medema, 2006;

Whitby & Palmateer, 1993). Additionally, if pathogens are associated with particles, they can be protected from radiation, which will decrease UV efficacy (Mamane-Gravetz & Linden, 2005; Örmeci & Linden, 2002). UV disinfection is therefore very sensitive to influent wastewater quality, and without effective pretreatment, low UV transmittance levels can prevent optimal disinfection.

Although UV disinfection is effective against all types of microorganisms, different doses are required to inactivate different species. Viruses are the most resistant to UV radiation, especially Adenoviruses, which can require UV doses between 69-109 for 2-log inactivation (Malley Jr. et al., 2004; Nwachuku, Gerba, Oswald, & Mashadi, 2005; Thurston-Enriquez, Haas, Riley, Gerba, & Jacangelo, 2003). Coliphages typically require 50 mJ/cm² for 2-log reduction (Clancy et al., 2002; Thurston-Enriquez et al., 2003), and 16 mJ/cm² are usually sufficient for 2-log reduction of feline Caliciviruses and 4-log reduction of Hepatitis A (Malley Jr. et al., 2004; Thurston-Enriquez et al., 2003). Bacterial spores also exhibit higher resistance to UV inactivation than other microorganisms (Hijnen, Van Der Veer, Beerendonk, & Medema, 2004). Lower UV doses are effective against bacteria and protozoan cysts. For example, 4-log inactivation has been observed with doses as low as 3-10 mJ/cm² for bacteria (Clancy et al., 2002; Malley Jr. et al., 2004) and 5 mJ/cm² for *Cryptosporidium* spp. (Clancy et al., 2000; Johnson et al., 2005). In order to inactivate all potential agents of disease, UV disinfection must reach doses that are effective against not only the highly-susceptible bacteria, but also the more resistant viruses and bacterial spores.

Ultraviolet Disinfection Units for Onsite Wastewater Treatment

Some ultraviolet disinfection (UVD) units have been specifically designed for onsite wastewater treatment sequences. Most of the UV bulbs used for wastewater disinfection are low-

pressure, low-intensity bulbs (13.8 PA pressure of mercury) that emit approximately 40% of their light at the germicidal wavelength of 253.7 nm (US EPA, 2002). The bulb is encased by a quartz sheath that protects the bulb from breakage and ensures that the bulb is kept at optimal temperatures (Anua International, 2014). Some models also include a Teflon sleeve that covers the quartz sheath, which is designed to reduce biofilm accumulation and simplify cleaning. The bulb and protective sleeves are placed in a 4-inch diameter ABS or PVC pipe, which limits the flow rate through the chamber and ensures that all wastewater is within a short distance of the UV bulb. Electrical circuitry connects the UV bulb to a power source, as well as to the bulb ballast and unit alarm. Different makes include different types of alarms, including visual and audial components. In some models, the alarm indicates a disconnection in the UVD unit's electrical circuit. Other models include an alarm that is connected to a sensor, which detects the strength of the UV radiation, and indicates insufficient UV bulb intensities.

UVD units must be installed after a pretreatment component as part of a treatment sequence. The sequence most often includes a septic tank, advanced treatment component (aerobic treatment unit or sand filter), UVD unit, and dispersal component. The pretreatment is necessary to reduce organic and solids levels in the wastewater so that UV dose is not reduced by low UV transmittance. UVD units are designed to disinfect wastewater that meets specific influent standards, for example the Salcor 3G unit requires that influent have BOD₅ and TSS levels below 30 mg/L (Salcor, Inc., 2011). Table 1 lists the proprietary treatment products registered in Washington State to be installed before UVD units.

Table 1. Proprietary Treatment Products with Ultraviolet Disinfection, Registered for Use in Washington State for Treatment Levels (TL) A–E and Treatment Level N^a

Product Name/Model	TLA	TLB	TLC	TLD	TLE	TLN
AdvanTex AX20RT, AX20 , AX25RT, AX20-2, AX20-3, AX20-4, AX100, AX100-2, AX-MAX, AX-MAX075-14, AX-MAX125-21, AX-MAX175-28 with Orenco UV units	✓	✓				✓
Aqua Safe AS600 + 4RN with UV Disinfection		✓				
ECOPOD E50 and E60 with Salcor 3G UV		✓				
ECOPOD E50NCA, E60NCA, E75NCA, E100NCA, E150NCA, E200-NFF, E250-NFF, E300-NFF, E50-N-IM1060, E60-N- IM1060, E75-N-IM1060 with Salcor 3G UV	✓	✓				
Enviro-Guard ENV-0.75 with Salcor 3G UV	✓	✓				
Fuji Clean CEN5, CEN7, CEN10 with Salcor 3G UV	✓	✓				
Hydro-Kinetic 600 FEU with AT 1500 UV	✓	✓				✓
Jet Inc. Model J-500 with the Salcor 3G UV	✓	✓				
LOWeFLOW™ System with the Salcor 3G UV LOT-LF-500, 600, 1000, 1500, 2000, 2500, 3000, 3500		✓		✓		
MicroFAST 0.5, 0.625, 0.75, 0.9, 1.5, 3.0, 4.5, 9.0 with Salcor 3G UV	✓	✓				✓
NuWater B-500 with Salcor 3G UV		✓				
NuWater BNR-500, BNR-600 with Salcor 3G UV	✓	✓				
Singulair TNT-500, TNT-750, TNT-1000, TNT-1250, TNT-1500, TNT-OP-500, TNT-OP-1000 with Norweco AT 1500 UV Unit	✓	✓				
Whitewater DF50 and DF60 with Salcor 3G UV	✓	✓				

^aTreatment Levels A through E have decreasingly stringent system performance testing levels for CBOD₅, TSS, and FC (only A-C). Treatment Level N also has a system performance testing level for total nitrogen (WAC 246-272A, Table III).

Source: WADOH, List of Registered On-site Treatment and Distribution Products, 2016.

Benefits and Limitations of Onsite Ultraviolet Disinfection

Ultraviolet disinfection has widespread applications due to its many benefits over other disinfection options. UV is effective against pathogens that are difficult to inactivate with other processes, for example *Cryptosporidium parvum* and enteric viruses (Clancy et al., 2000; Tchobanoglous et al., 2014). It also does not require the use of hazardous chemicals or create any

harmful disinfection byproducts (Tchobanoglous et al., 2014; US EPA, 2015). However, there are some limitations to consider when using UV disinfection, especially in OSSs.

Installation and maintenance of UVD units can be very expensive. Nationally, installation of a UVD unit is estimated to cost \$1,000-2,000, with continued costs for operation and maintenance averaging around \$250 per year: \$50-200 for inspection and maintenance, \$70-80 for bulb replacement, and \$35-40 for electrical power (Loomis et al., 2004; US EPA, 2002). Similar costs apply when installing UVD units in Washington State, although bulb replacement costs may be slightly higher (Thomas, 2018). The estimated total 60-year lifecycle cost for a UVD unit that is replaced every 10 years is \$7,600-11,000 (WERF, 2010). These costs can be a barrier to proper maintenance, but higher costs can accrue if systems are not maintained or must be completely replaced.

Regular maintenance is essential to ensure the ongoing performance of UVD units. Manufacturers recommend that service providers replace UV bulbs every 2 years and clean the bulb and protective sleeve at least once a year to minimize biofilm buildup (Norweco, Inc., 2014; Salcor, Inc., 2016). Mechanical equipment and electrical connections must also be inspected and any damage repaired (US EPA, 2002). To perform this maintenance, providers must have specialized knowledge of UVD units and electrical circuitry. A study performed in Pierce County, Washington found that without training, many maintenance providers did not have the expertise needed to ensure that UVD units were properly operating (Tacoma-Pierce County Health Department [TPCHD] & Washington On-site Sewage Association [WOSSA], 2014). Without sufficient maintenance, UVD units cannot fully function, and inadequate cleaning is a primary cause of malfunctions in disinfection systems (US EPA, 2015). Because maintenance often involves a lot of time, staffing, and monetary costs, the maintenance requirements of UVD

systems can limit their applicability and effectiveness, especially in regions where OSS maintenance programs are not well established.

Management and Maintenance in Western Washington

In Washington State, UVD units are intended to provide additional treatment at sites where few alternative options exist for sufficient wastewater treatment. The Washington State Administrative Code (WAC) restricts UVD unit installation to Category 1 systems in sensitive areas that require Treatment Level A or B, have an 18- to 24-inch vertical setback in Soils 2-3, and meet the 100-foot horizontal setback requirement (WAC 246-272A). Category 1 systems are designed to treat residential wastewater or wastewater of a similar quality (WAC 246-272A, Table I). Treatment Levels A and B include specific requirements of organic, solids, and microbiological reduction (see Table 2). Sensitive areas where OSS discharges could introduce increased public health risks include shellfish beds, sole source aquifers, wetlands, and recreational beaches (WAC 246-272A-0015(1)(b)). Soils 2-3 are coarse to medium sands, which may be loamy (WAC 246-272A, Table VIII). UV disinfection may not be used for repairs when OSSs do not meet horizontal setback requirements or to grant a waiver for reduced horizontal setbacks between soil absorption systems (SASs) and surface water, wells, or other sensitive areas (WAC 246-272A-0280(7); -0420(2)).

Table 2. Treatment Component Performance Testing Standards

Treatment Level	CBOD₅ (mg/L)^a	TSS (mg/L)^a	FC (CFU/ 100 mL)^b
A	10	10	200
B	15	15	1,000

^a30-day averages. ^b30-day geometric means

Source: WAC, Chapter 246-272A, Table III.

The WAC also includes several rules related to the installation and maintenance of advanced treatment systems in general and UVD units specifically. All OSSs except those

composed of only a septic tank and gravity-based SAS must be inspected at least annually or more frequently if required by the local health jurisdiction (WAC 246-272A-0270 (1)(d)(ii)). During these inspections and other visits, homeowners should ensure that maintenance providers maintain OSSs and complete any repairs needed to return the system to full operation (WAC246-272A-0270 (1)(f)). To facilitate easy maintenance and repair, OSSs with UVD units should be installed with an access point to the disinfection unit (WAC 246-272A-0238(1)(b)(v)). These rules are designed to ensure proper installation of UVD units and ongoing maintenance for optimal performance.

Local health departments in the counties bordering Puget Sound must implement local management plans to oversee OSS performance within their jurisdictions and ensure compliance with state requirements (WAC 246-272A-0015(1)). Local health jurisdiction requirements vary in the stringency of maintenance requirements, reporting protocols, and degree of oversight. One important difference between Pierce and Thurston counties is the frequency of UVD unit inspection. Tacoma-Pierce County Health Department (TPCHD) requires annual inspections of all high risk OSSs, including UVD units (TPCHD, 2014). Thurston County Public Health and Social Services (TCPHSS) has more stringent requirements. UVD units in Thurston County must be inspected semi-annually, and unit effluent must be sampled quarterly for fecal coliform concentrations (Thurston County Public Health and Social Services [TCPHSS], 2014). Thurston County has also designed Action Levels for fecal coliform sampling in OSSs assigned to different Treatment Levels. If fecal coliform levels in effluent samples exceed 2-times the treatment level standard in 2 or more of the past 4 samples, the homeowner and certified maintenance provider are required to troubleshoot and make any necessary repairs to improve UVD unit performance (TCPHSS, 2008).

Wastewater Treatment in OSSs with Ultraviolet Disinfection

Treatment Before UVD Unit

As wastewater flows through an OSS, each component provides additional treatment and removal of microorganisms. The quality of residential wastewater, the influent to the OSS, is difficult to predict because it depends on household activities and appliance use and is therefore highly variable between households and times of day (US EPA, 1980). The average daily flow has been estimated at 60-80 gallons per person per day, although many households that use water saving appliances have lower flows (DeOreo, Mayer, Dziegielewski, & Kiefer, 2016; Mayer, DeOreo, Towler, & Lewis, 2003). Peak wastewater flows generally occur in the morning (7-10am) and the evening (6-7pm; Butler, Friedler, & Gatt, 1995; University of Wisconsin, 1978). National estimates of residential wastewater quality for a household without a garbage disposal are given in Table 3. The use of a garbage disposal can significantly increase wastewater strength (University of Wisconsin, 1978; US EPA, 1980).

Table 3. Estimated Residential Wastewater Quality

TSS (30-day average) ^a	100–350 mg/L
BOD ₅ (30-day average) ^a	100–300 mg/L
Total coliforms ^b	10 ⁸ –10 ¹⁰ MPN/100 mL
Fecal coliforms ^b	10 ⁶ –10 ⁸ MPN/100 mL

Sources: ^aNSF/ANSI Standard 40, 2013. ^bUS EPA, 2002.

Manufacturers of advanced treatment units specify what types of pretreatment must precede their advanced component, and septic tanks are often required to provide treatment before wastewater flows to an aerobic treatment unit (WADOH, 2012). In a septic tank, fats, oils and grease float to the top of the wastewater and form a scum layer, while settleable solids fall to the bottom of the tank and become sludge (US EPA, 2002). Because pathogens are often associated with these particles, septic tanks provide some microbial reduction. Septic tank

effluent usually has 10^5 - 10^6 fecal coliform CFU/100 mL (University of Wisconsin, 1978). In a study of viral levels in septic tank effluent, F-specific (F+) coliphage levels varied between <1 PFU/100 mL and 10^5 CFU/100 mL, with a median of <1 PFU/100 mL, while somatic coliphage had a higher median of 120 PFU/100 mL (Hinkle et al., 2005). As these estimates show, microbial treatment is minimal in septic tanks, and additional treatment is necessary to remove potential pathogens from wastewater.

Most advanced treatment sequences with UVD units in Western Washington use aerobic treatment units (ATUs) to reduce organic and solids load before the wastewater is disinfected (WADOH, 2017). Multiple types of ATUs exist, including suspended growth treatment, attached growth treatment, or a combination of the two (US EPA, 2002). These units provide optimal conditions (dissolved oxygen [DO], pH, temperature, and nutrient load) for microorganisms naturally present in wastewater to degrade organic matter and other microorganisms. Wastewater treatment in the ATU depends on the solids and hydraulic retention time, and adequate levels of DO (>2 mg/L) must be maintained to allow for sufficient aerobic digestion (US EPA, 2000). If ATUs are properly maintained, they can produce effluent with carbonaceous biochemical oxygen demand (CBOD₅) levels below 25 mg/L, total suspended solids (TSS) below 30 mg/L, and fecal coliforms between 10^3 and 10^4 CFU/100 mL (US EPA, 2002). However, many studies have shown that ATUs often do not meet treatment standards due to poor system design, surge flows, or lack of continual maintenance, and effluent fecal coliform levels can exceed those expected from properly functioning units (Brewer, Lucas, & Prascak, 1978; Levett, Vanderzalm, Page, & Dillon, 2010; Maxfield, Daniell, Treser, & Vanderslice, 2003; Moelants, Janssen, Smets, & Van Impe, 2008; Sexstone et al., 2000; Wallace & Loudon, 2004). Therefore, many sites require additional disinfection of wastewater before it is discharged to a soil absorption system.

UVD Unit Treatment Performance

Previous testing and research studies indicate that UVD units are capable of reducing fecal coliforms to low levels, but that suboptimal disinfection may be an issue when UV bulbs malfunction or other parts of the unit are damaged. WADOH requires that all UVD units must be tested in combination with their pretreatment sequence according to the NSF/ANSI Standard 40 and the bacteriological reduction protocol (WAC 246-272A-0130). The NSF/ANSI testing measures effluent quality under the designed hydraulic loading, as well as under different stress loadings (e.g. vacation stress, laundry day stress, working parent stress, etc.; NSF Joint Committee on Wastewater Technology, 2013). The results from these tests show that UVD unit effluent complies with treatment level requirements (see Table 2). In a research study that examined the effectiveness of UVD units under simulated field conditions, Leverenz *et al.* found that a UVD unit provided greater than 4.4-log reduction of fecal coliforms and 5-log reduction of F+ coliphages when it was well-maintained and under optimal conditions. When the unit was not maintained and exposed to a stress period, biofilms developed on the protective sleeve before the manufacturer-recommended inspection time. However, the unit still provided a 3.1-log fecal coliform reduction (Leverenz, Darby, & Tchobanoglous, 2006). These studies indicate the capability of UVD units to provide high-quality effluent, which may be reduced if units are not consistently maintained.

Although these testing procedures and research conditions simulated different residential loading scenarios, it is difficult to artificially capture the variability in residential wastewater generation and the impact that it may have on UVD unit performance. Few studies have examined the effectiveness of UVD units under field conditions, but they provide additional insights that supplement the understanding of UVD unit performance. When examining a fixed

activated sludge treatment system followed by a UVD unit over a four-year period, Loomis *et al.* measured fecal coliform concentrations that ranged from 1 CFU/100 mL to 420 CFU/100 mL, with a geometric mean of 6 CFU/100 mL. The mean fecal coliform reduction achieved by the UVD unit was 2.5-log. The OSS included in this study received regular maintenance and repairs of electrical issues, which likely contributed to the consistency of the effluent quality (Loomis *et al.*, 2004). A larger survey of UVD units, which was led by the Kitsap Public Health District, reported frequent malfunctions of UVD units, with 44% of UV bulbs not burning at the time of service inspections (Kiess, 2014). The geometric mean fecal coliform level in pump chambers following malfunctioning units (934 CFU/100 mL) was higher than the geometric mean in systems with UV bulbs that were burning (342 CFU/100 mL; Kiess, 2014). These measurements from pump chambers are difficult to compare with previous results from UVD effluent, but they do indicate the need for better characterization of effluent fecal coliform levels.

The survey in Kitsap County, as well as anecdotal reports from certified OSS maintenance providers and local health department specialists, noted widespread bulb malfunctions, electrical damage, quartz breakage, and unit flooding (Kiess, 2014; WADOH, 2017). Water intrusion, protective sleeve damage, and electrical malfunctions have been observed elsewhere when evaluating individual UVD units (Leverenz *et al.*, 2006; Loomis *et al.*, 2004), but the prevalence of these issues in other regions has not been determined.

Treatment Provided after the UVD Unit

After wastewater is disinfected, a soil absorption system (SAS) disperses the wastewater and often provides additional treatment. Different dispersal systems can be used, including gravity-based drainfields, pressure distribution systems, mounds, or subsurface drip systems. A biomat develops at the interface between the distribution system and the natural soil, where

pollutants and pathogens are adsorbed to or filtered through organic deposits (Beal, Gardner, & Menzies, 2005). This represents the most significant contribution to treatment in the SAS, but contaminants are also adsorbed to soil particles or broken down by the soil microbiome as wastewater travels away from the SAS through the native unsaturated soil zone (US EPA, 2002).

Due to the high quality of effluent from advanced treatment systems, fecal coliforms can be completely inactivated within 12-23 inches (30-60 cm) of fine and course grained soils following these advanced systems (J. C. Converse & Tyler, 1998; J. Converse, Kean, Tyler, & Peterson, 1991). However, treatment in the SAS and the unsaturated native soil is highly dependent on soil properties and the depth to the saturated zone. Although treatment can exceed 5-log fecal coliform reduction and 2-log bacteriophage reduction in the top 23-53 inches (60-90 cm) of unsaturated soil, lower treatment is more common, and groundwater contamination does occur (Beal et al., 2005; Scandura & Sobsey, 1997). Because of the variability in soil characteristics and the treatment that can be expected at different sites, it is important to ensure that wastewater is receiving maximal treatment before it is discharged into SASs.

STUDY AIMS

The field effectiveness of OSSs that utilize UV disinfection is poorly understood, and OSS service providers report that UVD units frequently malfunction. To protect environmental quality and public health, it is important to determine whether OSSs with UVD units are achieving adequate treatment in the field. The goal of this study was to describe the bacterial and viral load in the effluent of in-field UVD units in Pierce and Thurston Counties, quantify the bacterial reduction by UVD unit disinfection, and assess field characteristics that may affect UVD unit performance.

Aim 1: Determine treatment levels achieved by OSSs with UVD units under field conditions using fecal coliform as an indicator for bacterial reduction and male-specific (F+) coliphage as an indicator for viral reduction. *We hypothesize that in at least 60% of OSSs, UVD units will reduce bacterial levels by 1-log, on average, achieving levels below 400 CFU/100 mL, and F+ coliphage levels will be reduced below 10 PFU/100 mL.*

- 1.1 Measure fecal coliform levels with and without UVD unit treatment and determine the mean reduction of bacterial load by UV disinfection under field conditions.
- 1.2 Describe distribution of effluent fecal coliform levels in field UVD units and estimate proportion of OSSs that meet treatment criteria (200 CFU/100 mL, 400 CFU/100 mL, and 1,600 CFU/100 mL).
- 1.3 Measure F+ coliphage in UVD unit effluent and determine prevalence.

Aim 2: Determine the associations between effluent bacterial load and observed wastewater quality, installation, and maintenance parameters. *We hypothesize that fecal coliform levels will be negatively associated with UV transmittance (with a 0.05 level of significance). We hypothesize that fecal coliform levels will be higher when the UV bulb is off.*

- 2.1 Assess correlation between wastewater physical quality and effluent fecal coliform levels.
- 2.2 Determine association between UV bulb malfunction and effluent fecal coliform levels.
- 2.3 Determine prevalence of installation, maintenance, and current functioning issues and assess associations with UV bulb malfunction.

Aim 3: Translate scientific findings for communication with all relevant stakeholders and public health practice.

- 3.1 Draft research findings for scientific publication.
- 3.2 Write final report and submit to Washington State Department of Health for use in evaluation of state regulations.
- 3.3 Design proper medium for communication with owners of OSSs with UVD units, including communication with study participants about study findings.
- 3.4 Present findings to professional environmental health associations (WOSSA, WESHA, NEHA).

The results of this study will inform public health practice for preventing microbiological contamination and human health risks. It will serve as evidence to support the reevaluation of Washington State regulations regarding design, installation, and maintenance of OSSs with UVD units. It will also enhance our understanding of ultraviolet disinfection in onsite wastewater treatment for removal of indicator bacteria and viruses.

FECAL COLIFORM CONCENTRATIONS IN EFFLUENT FROM ULTRAVIOLET DISINFECTION UNITS INSTALLED IN ONSITE WASTEWATER TREATMENT SYSTEMS

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 were collected from UVD units and pump chambers and tested for bacterial and physical wastewater quality. Field data were supplemented with data from retrospective quarterly 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). These results validate the importance of UVD units to reduce bacterial loads in addition to the contributions of other OSS characteristics to final effluent quality.

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 where OSSs and wells are in close proximity, untreated wastewater contaminate groundwater, causing drinking water 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, which leads to foodborne outbreaks and economic deficits (Geary & Davies, 2003). To avoid these negative outcomes of water pollution, it is important to ensure that OSSs are properly treating wastewater.

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 advanced 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). Inactivation of viruses requires the highest UV doses, (Gerba, Gramos, & Nwachuku, 2002), followed by bacterial spores (Hijnen et al.,

2004), whereas bacteria and protozoa are generally inactivated by lower doses (Malley Jr. et al., 2004).

Achieving adequate UV doses in UVD units depends on the complex interaction of OSS components and wastewater generation. UV dosage is determined by the contact time of the wastewater with the UV bulb, the intensity of UV radiation, and the wastewater's UV transmittance. The OSS's hydraulic loading influences the rate of wastewater flow and contact time with the UV bulb, 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 2 years (Norweco, Inc., 2014; Salcor, Inc., 2016). The organic loading and performance of pretreatment systems are also determinants of dose, as they influence the level of suspended and dissolved solids. Particles, dissolved salts, and organic compounds in the wastewater interact with UV light, causing high solids content to reduce UV transmittance (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 fecal coliform concentrations below 200 CFU/100 mL (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 (Leverenz et al., 2006; Loomis et al., 2004). Some studies observed biofilms growing on UV bulbs within 2 months, or sometimes at faster rates when the unit influent contained high solids (Leverenz et al., 2006; Weaver & Richter,

2003). 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 can be 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 geometric mean fecal coliform concentrations below 200 and 1,000 CFU/100 mL, respectively, under testing conditions (WAC 246-272A, Table III).

In addition to these 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 (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.

METHODS

Selection of Sampling Sites

The region for this study were two counties in Western Washington, USA, which provided a total of 2,177 UVD units in the target population. All owners of UVD units in this region were sent a letter of invitation, which offered a reimbursement of their next required maintenance fee (\$60–130) in return for participating in the study. The volunteers were primarily from one county, so participants from this county were randomly selected from all the volunteers, and additional participants from the second county were recruited via phone. 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, 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 and 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; D. S. Francy & Darner, 2012). For quality control, the laboratory used *Escherichia coli* as a positive control and *Enterobacter aerogenes* as a negative control. One duplicate sample was run each day to ensure consistency and accuracy.

Additional samples were collected and analyzed onsite for physical wastewater quality using direct-reading instruments. The measured wastewater parameters included temperature, pH, dissolved oxygen, conductivity, turbidity, and ultraviolet transmittance, 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 Thurston County, Washington, OSSs with UVD units must be inspected semiannually with quarterly effluent sampling (BH Consulting LLC, 2016). Inspection reports are collected through an online data management system, where reports are publicly available. Using Python code, the inspection reports and sampling results were extracted for all UVD unit inspections between 2010–2017 for a total of 125 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 were identical. 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. According to the National Shellfish Sanitation Program (NSSP) protocol, fecal coliform results that exceeded the upper limit of detection (LOD) were assigned a value of 1 whole unit above the limit, and results that were below the lower LOD were assigned a value of 1 whole unit below the limit (FDA 2015). If the limit of detection was 1 and there were no colonies detected, the result was recorded as 1. 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, a non-parametric correlation statistic that can be used for continuous data. 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 formula 1). Fecal coliform results were \log_{10} -transformed after adjusting for non-detects in the data (adding 1 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 \log_{10} -transformed bulb age on fecal coliform concentrations was performed for observations where the UV bulb was on.

$$Y_i^* = \beta_0 + \beta_1 * X_i + \varepsilon_i, \quad (1)$$

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)

$\varepsilon_{ij} \sim N(0, \Sigma)$:= 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:

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

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 Formula 2). Censored results that could not be classified as to action level exceedance were removed from the model (n=152).

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

RESULTS

Wastewater Quality of UVD Unit Effluent from Field Sampling

Researchers inspected 97 UVD units over a 3-month period between June and August. Freefall effluent samples were collected from 22 OSSs with UVD units, which did not have any indicators of significant malfunctions. The samples were collected at various times between 7:00 and 14:00, and the flow rates through the OSSs were generally low. Table 4 shows descriptive statistics for the freefall samples.

Table 4. Wastewater Quality of Freefall UVD Unit Effluent (n=22)

	Mean \pm SD ^a (min–max)	Spearman’s rho correlation with log-FC	p-value
Fecal Coliform (CFU/100 mL)^b	18.1 \pm 3.6 (<10–690)	–	–
Temperature [°C]	21.1 \pm 2.5 (16.7–25.6)	0.11	0.639
pH	6.7 \pm 0.8 (4.8–8.3)	-0.08	0.715
Dissolved Oxygen [mg/L]	6.8 \pm 2.0 (5.4–8.3)	-0.01	0.964
Conductivity [μS/cm²]	612 \pm 302 (227–1,308)	0.67	<0.001
Turbidity [NTU]^c	20 \pm 20 (0–60)	0.42	0.052
UV Transmittance [%]	44.5 \pm 17.7 (13.3–74.0)	-0.40	0.063
Flow Rate [mL/s]	10.2 \pm 9.7 (0.5–37.5)	0.41	0.063
OSS Age [years]	11.6 \pm 5.5 (1–22)		
Months Since Last Inspection	4.1 \pm 4.3 (0.5–19)		
Months Since Last Bulb Replacement	27.8 \pm 17.0 (2.0–67.6)		
Months Since Last Cleaning	4.8 \pm 5.6 (0.5–20.8)		
UVD Unit Make			
Salcor 3G	27%		
The Disinfecter	73%		
ATU Make			
BioMicrobics	73%		
Delta Environmental	14%		
Other	14%		

^aSD: standard deviation

^bReported statistics are geometric mean \pm GSD.

^cDue to imprecise measurements, turbidity measurements should be considered estimated values (within 10 NTU of the true value). It is unlikely that turbidity values are significantly biased (see Appendix A, Wastewater Sampling and Analysis for more detail).

Fecal coliform levels were measured with the UV bulb turned off in 17 UVD units. The geometric mean (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

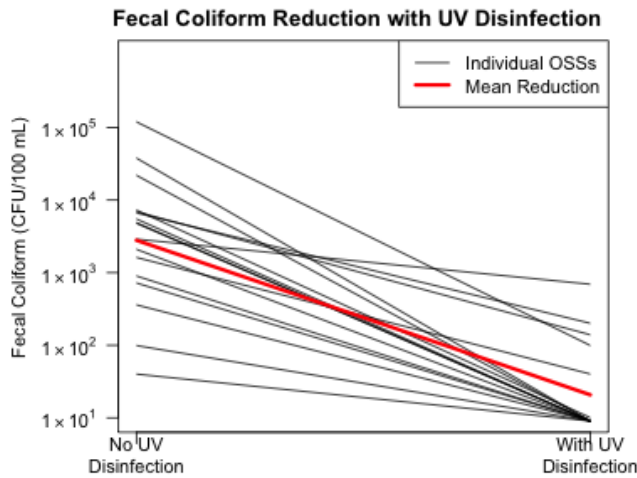


Figure 1. Individual and Mean Fecal Coliform Reductions in Ultraviolet Disinfection Units, as Characterized by Sampling UVD Unit Effluent with UVD Unit Turned On and Turned Off

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; see Figure 1). 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 these correlations 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, <10–>2×10⁶ CFU/100 mL) was higher for pump chamber samples than for freefall effluent samples. The descriptive statistics for pump chamber fecal coliform concentrations

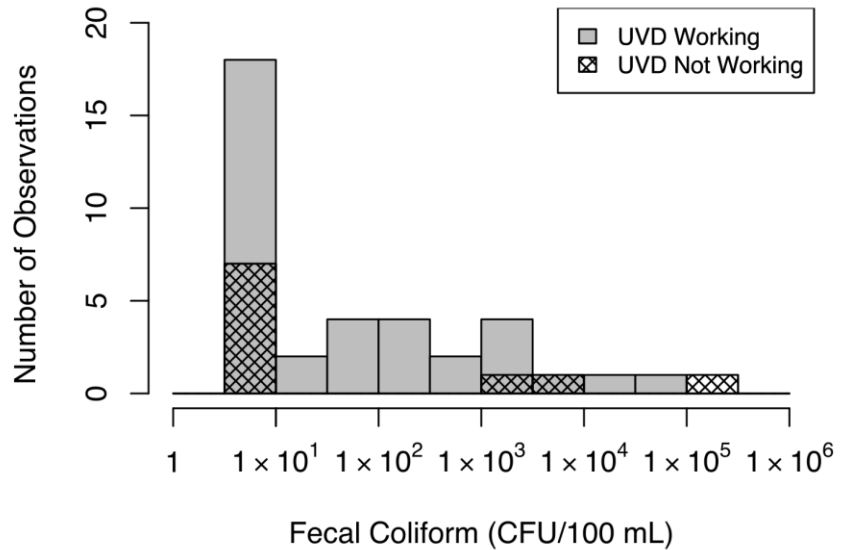


Figure 2. Distribution of Fecal Coliform Concentrations in Pump Chambers, Stratified by OSSs With and Without Working UVD Units

grouped by UV bulb status are given in Table 5. Among OSSs with malfunctioning UVD bulbs, 3 of the 5 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 (see Figure 2). 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.

Table 5. Fecal Coliform Concentrations in Pump Chambers Following UVD Units (in CFU/100 mL)

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

^aNumber of samples with fecal coliform concentrations greater than the limit of detection (10 CFU/100 mL for most samples)

^bUV bulbs classified as not working if UV bulb was off or had high biofilm deposit.

^cUV bulb status could not be determined.

Wastewater Quality in Retrospective Quarterly Compliance Samples

Quarterly sampling reports from 2010–2017 included 2,711 records of fecal coliform measurements. Of these, 2,377 (88%) were taken when the UV bulb was not deficient, 65 (2%) when the UV bulb was deficient (off or effluent bypassing unit), and for 269 (10%) of the samples, 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, $<1-8.0 \times 10^4$ CFU/100 mL) and 297.3 CFU/100 mL when the UV bulb was deficient (GSD= 10.6, $<1-5.9 \times 10^4$ CFU/100 mL; see Figure 3). Estimates from the multivariate Tobit regression model show a significant

association between fecal coliform concentrations and UV bulb deficiency (see Table 6). 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 (GM ratio 95% confidence interval (CI)=36–428, p-value <0.001). The predicted GM fecal coliform concentration in effluent from OSSs without any deficiencies is 6.1 CFU/100 mL, and the predicted GM fecal coliform concentration in effluent from OSSs with a UV bulb deficiency, but without other OSS deficiencies, is 745 CFU/100 mL. A

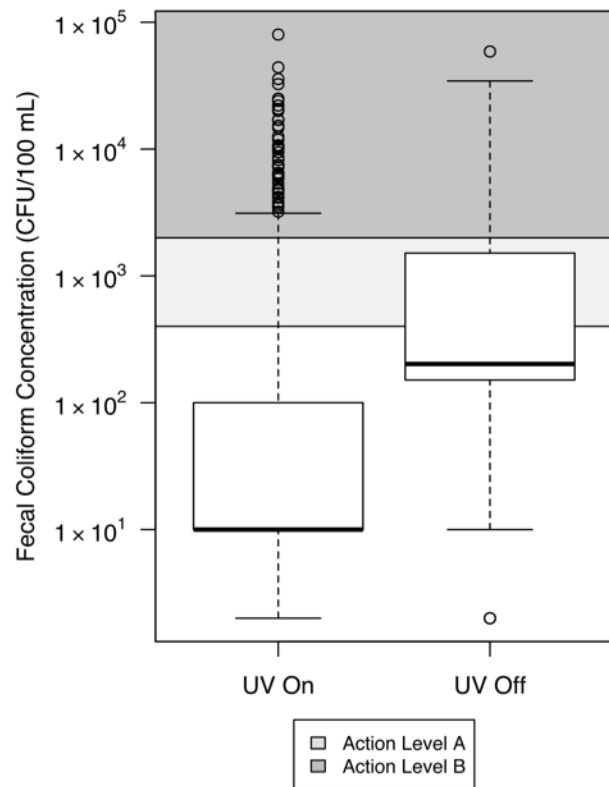


Figure 3. Fecal Coliform Concentrations in Onsite Sewage Systems with UV Disinfection Units, Divided by Presence of UVD Deficiency and Compared to Regulatory Action Levels (Action Level A=400 CFU/100 mL, Action Level B=2,000 CFU/100 mL)

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).

Table 6. Multivariate Tobit Regression Model Estimates for Geometric Mean Fecal Coliform Concentrations

	Raw Model			Exponentiated Model		p-value
	Estimate	Standard Error	95% CI ^a	Estimate	95% CI	
Intercept	0.782	0.101	0.58–0.98	6.05	3.84–9.55	< 0.001
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

^a95% confidence interval
^bUV bulb off or OSS flow bypassing the UVD unit
^cDeficiency in OSS component other than UVD unit. Includes aerator malfunction, overdue pumping, and lack of electrical power to the OSS.

Among the fecal coliform results from quarterly compliance samples, 197 (7.7%) exceeded 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 7 depicts the exceedance prevalence stratified by UV bulb status and OSS action level.

Table 7. 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

Logistic regression analysis indicated that among OSSs that have the same deficiency status, 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 was properly functioning (95% CI: 4.03–13.9, p-value<0.001; see table 8).

Table 8. Multivariate Logistic Regression Model Estimates for Exceedance of Fecal Coliform Action Levels

	Raw Model		Exponentiated Model		p-value
	Estimate	Standard Error	Estimate	95% CI ^a	
Intercept	-2.65	0.09	0.07	0.06–0.08	< 0.001
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

^a95% confidence interval
^bUV bulb off or OSS flow bypassing the UVD unit
^cDeficiency in OSS component other than UVD unit. Includes aerator malfunction, overdue pumping, and lack of electrical power to the OSS.

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 produce effluent with low fecal coliform levels that meet treatment standards. 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 (Leverenz et al., 2006; Loomis et al., 2004). Because of the low flow rates 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 of these units, but these issues 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.

Bacterial effluent quality was strongly correlated with conductivity, and its correlation with turbidity was marginally statistically significant. As noted by Leverenz et al. (2006), wastewater with high solids content is difficult to disinfect with ultraviolet disinfection. Conductivity and turbidity are surrogate measures of solids content, and low levels indicate that the pretreatment sequence is reducing solids before wastewater reaches the UVD unit or that the OSS influent had low solids content to begin with. 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 (Levett et al., 2010; US EPA, 2002). 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 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 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, so the fecal coliform concentrations that the pump chamber is discharging may be higher than those measured in UVD unit effluent. 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 (J. C. 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 concentrations in 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 ($SD=3.4 \times 10^4$ 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 (J. C. 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 pump chamber dosing, and the hydraulic and organic load of OSS influent.

UVD Unit Effluent Quality Characterized from Regulatory Sampling

When considering retrospective compliance samples from OSSs with UVD units, 8% of the fecal coliform results exceeded the OSS's action level standard. However, this proportion was significantly higher when looking only at UVD units where the UV bulb was deficient

(36%). 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 biofilm buildup, could have contributed to the exceedances observed in some properly functioning UVD units. 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 geometric mean fecal coliform concentration for deficient UVD units (745 CFU/100 mL) that exceeded action level A, but not higher action levels. This indicates that proper functioning of UV bulbs is especially important for sites that require Treatment Level A, and 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. All 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 flow rates. 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.

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 reporting during OSS inspections 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.

CONCLUSION

This study confirmed that UVD units provide high-quality effluent when they are properly functioning and installed after pretreatment sequences that reduce solid loads to appropriate levels. However, in cases where UV bulbs are off, 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 take special

efforts to ensure that UVD units are functioning properly and providing disinfection. Although this study emphasizes the importance of UVD units to accomplish adequate wastewater treatment, bacterial regrowth in pump chambers may introduce additional risks of poor-quality effluent discharge, and additional studies are needed to clarify the contributions of other wastewater treatment components when installed in combination with UVD units.

OPERATION AND MAINTENANCE FACTORS IMPACTING PERFORMANCE OF ULTRAVIOLET DISINFECTION UNITS IN ONSITE SEWAGE SYSTEMS

ABSTRACT

Long-term performance of onsite sewage systems (OSSs) depends highly on the operation and maintenance provided. In response to reports of frequent ultraviolet disinfection (UVD) unit malfunctions, this study evaluated 97 UVD units in Western Washington to determine the prevalence of malfunctions and examine possible contributions to inadequate performance. Disinfection was inhibited in 25% of the observed units due to UV bulbs being off, and dense biofilms likely reduced disinfection in an additional 4% of UVD units. Other common issues were installation of the UVD unit on a non-dedicated electrical circuit (81%), inadequate cable slack between the UV bulb and access point (18%), damaged protective sleeves (24%), and electrical damage (15%). At least 77% of the UVD units had not been maintained according to manufacturer recommendations within the last 2 years. A strong pattern was observed when comparing UVD units at a county-level, with a much lower prevalence of malfunctioning units in a county with stringent maintenance requirements and oversight. The study's results suggest that when UVD units are installed, correct installation and intensive management plans are necessary to prevent suboptimal wastewater treatment and minimize public health risks.

INTRODUCTION

Ultraviolet Disinfection for Advanced Onsite Wastewater Treatment

Although onsite sewage systems (OSSs) provide important treatment of wastewater in regions without municipal sewers, they impact groundwater quality and are potential sources of fecal contamination (S. P. Carroll et al., 2004; Schneeberger et al., 2015). Many cases of public health risks from OSS discharges have been documented, including contamination of coastal

waters and shellfish beds and drinking-water associated outbreaks due to groundwater contamination (Bremer & Harter, 2012; Duda & Cromartie, 1982; Fong et al., 2007; Lipp et al., 2001; Miller & Ortiz, 2001). Risks of pollution from OSSs are especially high in regions where poor soil quality limits the wastewater treatment. In these cases, which represent about two thirds of U.S. land (US EPA, 2002), advanced treatment is necessary. As population grows and residential development expands into areas unsuitable for conventional OSSs, the demand for advanced treatment will also increase.

The Washington State Department of Health estimates that more than 65,000 OSSs in the Puget Sound region are located within areas of special concern for shellfish industry and water quality (WADOH, 2014). As a strategy to protect environmental and public health, some of these locations now require advanced onsite wastewater treatment, which can include ultraviolet disinfection (UVD) units. Since the late 1990s, over 6,000 UVD units have been installed in Washington State (WADOH, 2017).

Benefits and Limitations of Ultraviolet Disinfection

Ultraviolet (UV) disinfection inactivates pathogens by damaging nucleic acids. When performing optimally, onsite UVD units achieve UV doses that inactivate most viruses, bacteria, spores, and protozoan cysts (Duizer et al., 2004; Gerba et al., 2002; Hijnen et al., 2004; Malley Jr. et al., 2004). UVD units with pretreatment sequences used in Washington State have met National Sanitation Foundation/American National Standards Institute (NSF/ANSI) Standard 40 requirements for bacteriological reduction (30-day geometric mean fecal coliform below 200 CFU/100 mL; WADOH, 2012) and are capable of providing high quality effluent.

Pretreatment sequences, often a septic tank and an aerobic treatment unit or other advanced treatment product, are necessary to reduce solids in wastewater before it is disinfected.

Particles, dissolved salts, and organic compounds must be reduced because they can absorb or reflect UV light, preventing adequate doses from reaching microorganisms (US EPA, 2003; Whitby & Palmateer, 1993). Additional limitations include the high cost of installation and ongoing operation, as well as extensive maintenance requirements (Tchobanoglous et al., 2014).

UVD unit manufacturers recommend periodic replacement of UV bulbs and checks for electrical or mechanical damage, scaling, and biofilm buildup (Norweco, Inc., 2014; Salcor, Inc., 2016; US EPA, 2002). Washington State requires that UVD units are inspected at least annually (Washington Administrative Code, 2010), and local health jurisdictions within areas of special concern have management plans to maximize compliance with this rule. Of the two local health jurisdictions included in this study, one requires annual inspections by a certified maintenance provider, whereas the other requires that UVD units be inspected semiannually and effluent be sampled quarterly for fecal coliforms (BH Consulting LLC, 2016; TPCHD, 2014).

Despite successful removal of microorganisms under testing conditions, concerns have arisen regarding the effectiveness of UVD units when installed in the field. Previous studies, local health jurisdiction reports, and anecdotal accounts from maintenance providers indicate that some UVD units malfunction and may not be providing disinfection (Kiess, 2014; Leverenz et al., 2006; Loomis et al., 2004; Weaver & Richter, 2003). Issues observed in these studies include bulb failures, problems with alarms, electrical failures, problems with protective coverings, and flooding of unit housing (Kiess, 2014; Leverenz et al., 2006; Loomis et al., 2004; Weaver & Richter, 2003). To assess the field effectiveness of UVD units, this study aimed to determine the prevalence of UVD unit malfunctions and to examine possible risk factors for suboptimal performance.

METHODS

Participant Recruitment

All owners of UVD units in two Western Washington counties, a total of 2,175 units, received a letter about the research study that invited them to volunteer in exchange for a reimbursement of their next required maintenance fee (\$60-130). Because the number of Pierce County volunteers (210) exceeded the target sample size, 65 volunteers were randomly selected to participate in the study. Additional recruitment was necessary in Thurston County, so participants were also recruited by phone call. The final sample size was 97 UVD units, 65 from Pierce County and 32 from Thurston County. All studied UVD units were assigned a random ID to ensure confidentiality.

The invitation letter included a questionnaire with 6 questions about the information that owners have about their UVD unit. The questionnaire was developed by reviewing previous surveys about homeowner perceptions of OSS maintenance and adding questions specific to UVD units (Clallam County Health and Human Services, 2014; Elway Research, Inc., 2008; McNulty & Lindbo, 2004; Sherman, Varnadore, & Forbes, 1994; U.S. Geological Survey, 2004). A draft of the questionnaire was tested with 5 OSS owners to evaluate clarity and preciseness of questions before the final version was sent to study participants.

Onsite Observations

Over a 3-month period between June and August, UVD units were inspected for indicators of installation and performance issues, which had been identified in previous studies and consultations with industry experts (Leverenz et al., 2006; Loomis et al., 2004). They addressed the OSS control panel, electrical connection to the UVD unit, UVD unit housing, and

UV bulb with protective sleeves. The level of biofilm buildup on the protective sleeve was classified on a 4-level scale: None, Low, Medium, or High.

Review of Maintenance Records

Data about OSS characteristics and maintenance inspections were compiled from lists provided by local health jurisdictions. Using service reports publicly available in the database management system OnlineRME, all dates after 4/3/17 were adjusted to the most recent date preceding 4/3/17, and all dates before 2010 were removed to create a consistent reporting timeframe. For OSSs evaluated in this study, the inspection dates were updated to reflect the most recent maintenance before the study's field evaluation. This information was then combined with data from study evaluations, and the accuracy of the data compilation was checked for 10% of the evaluated systems.

Statistical Analysis

Study data were analyzed using non-parametric tests and logistic regression models. The prevalence of observed issues was determined for each county separately and for all data combined. Prevalence was calculated by dividing the number of occurrences of each issue by the total number of OSSs for which that issue could be observed. 95% confidence intervals were determined using Pearson's chi-square tests of equal proportions.

Associations between UV bulb malfunction and the other observed issues with installation, maintenance, and current performance were examined to evaluate possible risk factors for bulb malfunction. Associations were examined in isolation and combined with other predictors of interest to adjust for confounding. Fisher's exact tests were conducted for all binary variables, and univariate logistic regression models with robust standard errors were run for non-binary variables. Non-binary predictor variables were standardized for comparison to binary

variables by dividing each result by two times the standard deviation (Gelman, 2008). To examine the effect of all predictors combined on UV bulb malfunction, an L1 regularized logistic regression model (also known as lasso regression) was run. Cross validation was used to determine the lambda correction factor that would create a model with the smallest mean-squared error and the model with the smallest mean-squared error within one standard error of the minimum (Hastie & Qian, 2016; Krstajic, Buturovic, Leahy, & Thomas, 2014). 18 observed indicators of suboptimal performance were included as predictors in the model: UVD unit on non-dedicated circuit, power switch for UVD unit inaccessible, electrical connection to UVD unit unprotected, electrical corrosion or damage, inadequate cable slack, cracks in UVD unit housing, UVD unit unprotected from flooding and debris, leaking UV bulb protective sleeve, level of biofilm deposit on UV bulb protective sleeve, location of UVD unit, UVD unit make, ATU make, age of OSS, number of bedrooms served by OSS, months since last OSS inspection, months since UV bulb last replaced, months since UVD unit last cleaned, and months since OSS last pumped.

Qualitative Focus Group and Interview

To gain a more complete understanding of installation and maintenance practices, a focus group and semi-structured interview were conducted with industry experts from both counties in the study area. Certified maintenance providers and installers were asked to provide insight about their experiences with UVD units, barriers to maintenance, and how to improve UVD unit performance.

RESULTS

Description of Observed UVD Units

Of the 97 UVD units observed, 25% were not burning and thus unable to provide disinfection. An additional 4% of the bulbs were covered with dense biofilms that likely inhibited UV disinfection. Descriptions of these units and the proportions of different issues are given in Table 9.

The most common installation issues were installation of the UVD unit on a combined electrical circuit with the aerobic treatment unit or distribution pump (81%) and inadequate cable slack between the UV bulb and access point (18%). 24% of the observed UVD units had damaged or leaking protective sleeves, and 15% of the electrical components were corroded or damaged. Among the units with LED indicator lights, 30% were incorrectly indicating the status of the UV bulb.

Table 9. Characteristics of Ultraviolet Disinfection Units and Observed Indicators of Suboptimal Performance

	% OSSs in Pierce Co. (n=65)	% OSSs in Thurston Co. (n=32)	Total % (n=97)
Description of Inspected UVD Units			
Age [Years]^a	10.6 ± 4.5 (2-20)	12.0 ± 5.6 (1-24)	11.1 ± 4.9 (1-24)
Number of Bedrooms^a	3.4 ± 0.7 (2-5)	2.9 ± 1.0 (0-4)	3.2 ± 0.8 (0-5)
UVD Make			
Salcor 3G	22 (34%)	9 (28%)	31 (32%)
The Disinfector	38 (59%)	23 (72%)	61 (64%)
Norweco	4 (6%)	0	4 (4%)
ATU Make			
BioMicrobics	33 (52%)	18 (56%)	51 (54%)
Delta Environmental	25 (40%)	8 (25%)	33 (35%)
Other	5 (8%)	6 (19%)	11 (12%)
UV bulb off	22 (39%)	0	22 (25%)
Installation Issues			
UVD unit inaccessible	6 (9%)	0	6 (6%)
UVD unit on non-dedicated circuit	54 (84%)	24 (75%)	78 (81%)
Inadequate cable slack	16 (29%)	0	16 (18%)
Power switch inaccessible	9 (14%)	2 (6%)	11 (12%)
UVD housing unit unprotected from flooding or debris	8 (14%)	2 (7%)	10 (11%)
UV bulb with protective sleeve inaccessible	6 (10%)	2 (6%)	8 (9%)
UVD unit not protected from power disconnection	5 (8%)	1 (3%)	6 (7%)
Issues with Current Functioning of Key Components			
LED indicator incorrect^b	9 (38%)	1 (11%)	10 (30%)
Damage or leakage in protective sleeve	14 (28%)	5 (17%)	19 (24%)
Electrical corrosion or damage	12 (21%)	1 (3%)	13 (15%)
High biofilm deposit on protective sleeve	8 (16%)	0	8 (10%)
Leaks/cracks in UVD housing unit	3 (5%)	2 (7%)	5 (6%)
<i>Unless otherwise noted, reported statistics are counts and percentages of total systems where the indicator of interest was observed.</i>			
<i>^aReported statistics are mean ± standard deviation, (minimum – maximum).</i>			
<i>^bNot all UVD units have an LED indicator light. This is the percent of malfunctioning LED indicators in all units with an LED indicator (n=24 in Pierce Co., n=9 in Thurston Co.).</i>			

Most issues were more prevalent in Pierce County than in Thurston County. This dichotomy is well-demonstrated with the difference in prevalence of UV bulbs that were off: 39% were not burning in Pierce County, whereas all observed bulbs in Thurston County were on. County-level differences in the prevalence of other common issues is displayed in Figure 3.

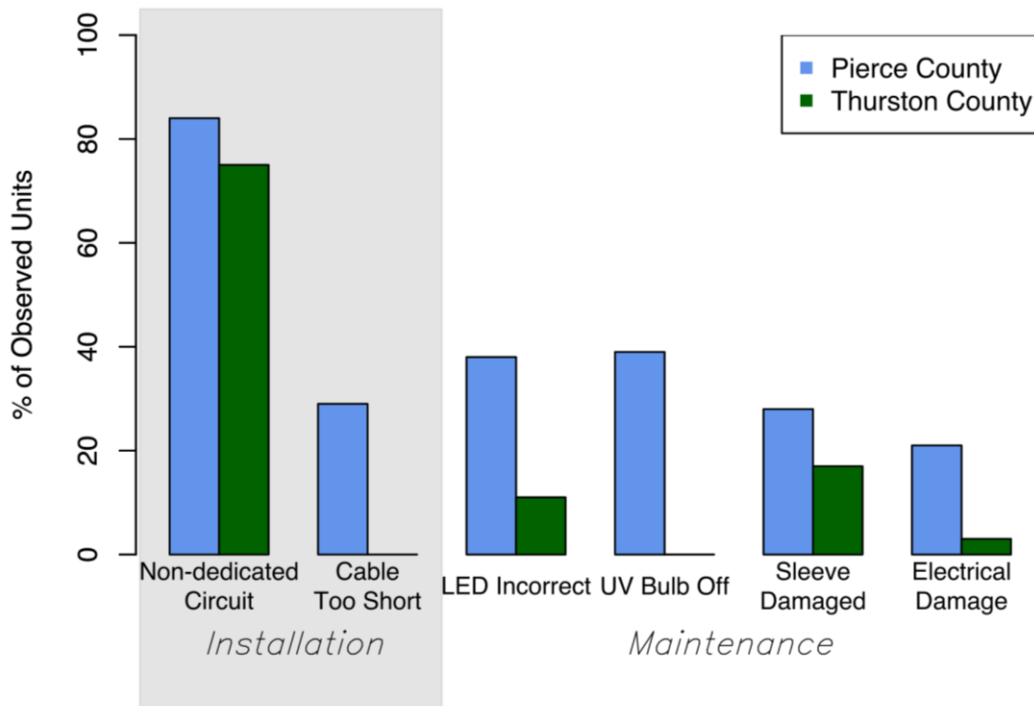


Figure 3. County-level Differences in Installation and Maintenance-Related Issues of Ultraviolet Disinfection Units

At least 77% of the observed UVD units had not received manufacturer-recommended maintenance in the past 2 years. 51% of the UV bulbs had not been replaced within the last 2 years, and 44% of the protective sleeves had not been cleaned within the last year. Maintenance patterns varied between the two counties, with more recent maintenance occurring in Thurston County than in Pierce County (see Table 10). Compared to the target population, the OSSs included in the study were on average maintained more recently than the average maintenance times for all UVD units in the study area (see Appendix 4. Representativeness of Study Sample).

Table 10. Time, in Months, since Most Recent Maintenance Performed on UVD Units

	Pierce Co. (n=65)	Thurston Co. (n=32)	All (n=97)
OSS Inspection ^a	6.8 ± 3.7 (0-12.8), 6.9	4.2 ± 4.8 (0.1-20.9), 2.9	6.0 ± 4.3 (0-20.9), 5.4
<i>% Out of Compliance^b</i>	9.2	22.6	13.5
UV Bulb Replacement ^c	35.8 ± 22.7 (6.0-83.3), 34.6	28.8 ± 16.9 (2.0-67.6), 20.1	33.5 ± 21.1 (2.0-83.3), 29.6
<i>% Longer than 2 Years</i>	58.1	35.0	50.8
UV Protective Sleeve Cleaning ^d	20.1 ± 18.9 (3.7-81.1), 13.5	5.4 ± 6.3 (0.1-20.9), 3.1	15.4 ± 17.3 (0.1-81.1), 13.5
<i>% Longer than 1 Year</i>	57.8	13.3	43.6
<i>Reported statistics are mean ± SD (min-max), median.</i>			
<i>^aData missing for 1 unit in Thurston Co.</i>			
<i>^bFor Pierce Co., OSS inspection timing was out of compliance if there was no inspection in the past year. For Thurston Co., OSS inspection timing was out of compliance if there was no inspection in the past 6 months.</i>			
<i>^cData missing for 22 units in Pierce Co., 12 units in Thurston Co.</i>			
<i>^dData missing for 1 unit in Pierce Co., 2 units in Thurston Co.</i>			

Logistic Regression Models

Univariate logistic regression models indicate that electrical damage and biofilm levels on protective sleeves were most strongly associated with UV bulb malfunction (see Table 11). L1 regularized logistic regression models confirmed that these issues were the strongest predictors of UV bulb malfunction. Biofilm deposit was the only non-zero coefficient in the model with the smallest cross-validated error within one standard error of the minimum, and it explained 4% of the variability in UV bulb malfunction. In other words, even with a large penalization factor, biofilm deposit remained a significant predictor of UV bulb malfunction. In the model with the minimum cross-validated error, biofilm deposit level, electrical damage, and leaks in the UVD housing unit had non-zero coefficients, and together explained 28% of the variability in UV bulb malfunction. Electrical damage and leaks in the housing unit were not as strongly associated with UV bulb malfunction as biofilm deposit, but their relationship with UV bulb malfunction was stronger than that of the other UVD unit issues observed during the study.

Table 11. Odds Ratios for UV Bulb Malfunction (UV Bulb Off)

	Unstandardized OR (95% CI)	Standardized^a OR (95% CI)	p-value
Electrical corrosion or damage	13.5 (2.87-88.0)		<0.001
UV bulb inaccessible	3.05 (0.209-44.6)		0.269
>1 year since UV unit cleaned	2.16 (0.724-6.61)		0.136
Inadequate cable slack	2.01 (0.516-7.29)		0.34
Leaks in UVD housing unit	2.01 (0.158-18.9)		0.599
Biofilm deposit rank	2.98 (1.64-5.42)	8.39 (2.63-26.8)	<0.001
# of bedrooms	1.82 (0.940-3.51)	2.62 (0.904-7.61)	0.0753

^a*Categorical and continuous variables were divided by 2 standard deviations to compare the OR magnitude to that of binary variables.*

Septic Owner and Maintenance Provider Perspectives

During the focus group and interview, industry experts confirmed the observed barriers to ongoing maintenance. According to maintenance providers, inappropriate installations prevent easy access for maintenance, and UVD unit components which are not watertight or easily break are difficult to maintain. Service providers also indicated that homeowners are disinterested and hesitant to invest in replacement parts, especially without a quantitative measurement of effluent quality that shows the need for repairs. The questionnaires included in this study also highlighted that although homeowners are interested in learning more about their UVD units, 77% do not have manuals for operation and maintenance, and 56% rely completely on their maintenance providers to ensure that their UVD unit is operating properly. Those septic owners who do personally check their UVD units often use inappropriate indicators of proper UVD unit performance.

DISCUSSION

Suboptimal Performance of UVD Units

Installation, maintenance, and current functioning issues were highly prevalent in the observed UVD units. The prevalence of UV bulbs in Pierce County that were off (39%) is

comparable to the 44% of UV bulbs that were not burning during yearly inspections by maintenance providers in Kitsap County, Washington (Kiess, 2014). The problems with protective sleeve damage, biofilm buildup, and electrical disconnections have also been noted in previous studies (Leverenz et al., 2006; Loomis et al., 2004; Weaver & Richter, 2003). Because the sample was composed of units that had been maintained more recently than the average for UVD units in the study area, it is likely that these issues, especially those related to maintenance and current functioning, are more prevalent in Western Washington than the proportions observed in the study. The high prevalence of damaged or improperly functioning UVD unit components indicate a potential for improved design, installation, and maintenance of units to protect against damage. For example, manufacturers can improve performance by developing more watertight sealing of electrical circuits, followed by training about electrical installations for UVD unit installers. Biofilm buildup on protective sleeves should also be reduced, potentially by altering design or by ensuring consistent cleaning.

In a concurrent study, it was determined that on average, the geometric mean fecal coliform in effluent from UVD units with malfunctioning bulbs is 122% greater than the geometric mean fecal coliform in effluent from units with functioning bulbs (Jackson et al., unpublished). Furthermore, if a bulb's UV radiation has declined, the UV dose may not be adequate for microbial disinfection, even if it is visibly glowing. UV intensity was not measured during this study, so burning UV bulbs with low intensity were not captured, and the prevalence of UV bulbs not disinfecting wastewater may be even greater than those indicated by the UV bulb being off. Because UVD units are designed to reduce microbial load, the high proportion of malfunctioning bulbs introduces a risk of pathogen release into the environment and potential human exposure.

Inadequate Maintenance

Many of the observed UVD units had not been maintained according to manufacturer recommendations. In some cases, the OSS installation prevented access to the UVD unit (6%) or the UV bulb and protective sleeve (9%), and inadequate cable slack limited access to the bulb in 18% of the observed units. Inadequate access is a significant barrier to providing sufficient maintenance. However, maintenance was also lacking in OSSs where UVD units were well-accessible. Although this study did not show a statistically-significant relationship between maintenance patterns and UV bulb malfunction, maintenance likely contributes to the other observed risk factors. The lack of UV bulb cleaning may have led to the high biofilm deposits that were strongly associated with UV bulbs being off, an indicator of the lack of UV bulb replacement. The association between electrical damage and UV bulb malfunction also indicates that it is important to repair units and keep bulbs properly connected and functioning. Additionally, the correlation between conductivity and fecal coliform concentrations observed in a concurrent study indicate that maintenance of both the UVD unit and the pretreatment components are important to ensure that OSS effluent has low microbial loads (Jackson et al., unpublished).

The questionnaires and interviews included in this study also emphasized the importance of collaborations between certified maintenance providers and septic owners to provide maintenance. Increasing owner education about UVD units may encourage owners to collaborate with maintenance providers and take more initiative to ensure proper operation and maintenance. Without adequate maintenance, it is likely that UVD units will continue to malfunction at high rates, so barriers to maintenance need to be addressed as ongoing maintenance requirements and programs are put into place.

Local Health Jurisdiction Management

The differences between county-level prevalence of UVD unit installation, maintenance, and functioning issues indicate that local health jurisdiction supervision and enforcement of OSS maintenance is an important factor in ensuring reliable functioning of UVD units. Although differences were observed in the prevalence of both installation- and maintenance-related issues, the differences were greater for maintenance issues and reparable installation problems that impact the ability to perform ongoing maintenance. In both study counties, a high proportion of UVD units were installed without a dedicated circuit breaker, which is an installation recommendation intended to protect against electrical malfunctions. This indicates that installation inadequacies that are difficult to repair in retrospect need to be corrected at the time of first inspection. In contrast to installation issues, the low prevalence of maintenance issues in Thurston County indicates that with more frequent inspections, maintenance providers can respond to UVD unit malfunctions and provide necessary repairs within a shorter period. Additionally, the quarterly sampling of UVD unit effluent provides a quantitative assessment of the effluent and a more objective measure of unit performance. Interviewed service providers supported effluent sampling as a strong motivator that can encourage homeowners to pursue necessary cleaning and repairs.

With less stringent assessment and reporting mechanisms in Pierce County, more malfunctions were observed. In a previous study on potential reasons for insufficient maintenance, authors noted that inspection reporting was often incomplete and that service inspections were conducted by maintenance providers without expertise in specialized systems (TPCHD & WOSSA, 2014). While strengthening the health department infrastructure to ensure that adequate maintenance is performed, UVD unit reliability could be improved with UVD unit

installation and maintenance training, clarification of maintenance requirements for advanced OSSs, and consistent, detailed reporting mechanisms for better oversight of maintenance and repairs.

Study Limitations and Suggestions for Future Research

Many environmental and social factors can impact UVD unit performance, and it is difficult to account for them all in a population study. For example, this study did not consider differences in influent wastewater quality, homeowner engagement in proper operation and maintenance, or long-term maintenance provided by service providers. Expanding this study with an experimental approach that compares UVD unit performance under similar conditions while changing key factors that influence performance would provide additional insight into UVD unit malfunction. Additionally, it is important to consider the impact that UV bulb malfunctions can have on risks to public health, including pathogen contamination of groundwater or shellfish beds. One potential tool to assess these impacts could be a quantitative microbial risk assessment to consider the transmission routes that could expose humans to pathogens from UVD unit discharges and the reduction in negative health effects that is provided by UV disinfection.

CONCLUSION

This population-based survey of UVD units in Western Washington observed several installation, maintenance, and current functioning issues. It also identified potential risks factors associated with UV bulb malfunction, including biofilm buildup, electrical damage, and county-level management. The patterns observed indicate that proper operation and maintenance are important to ensure reliable functioning of UVD units. To improve performance of currently installed units and ensure proper functioning of future installations, clear requirements for local

management plans and maintenance schedules should be enforced. Additionally, UVD units should only be installed when maintenance can be ensured, and maintenance providers should receive training about the important components of UVD units, especially the electrical wiring and bulb's protective sleeves. By proactively preventing UVD unit malfunctions, homeowners, maintenance providers, local health jurisdictions, and state health departments can collaborate to maintain environmental quality and protect public health.

MALE-SPECIFIC COLIPHAGE IN ONSITE SEWAGE SYSTEMS WITH UVD UNITS

Rationale for Male-Specific Coliform Analysis

Currently, fecal coliform is the most commonly used indicator of fecal contamination, and it is measured extensively to monitor public exposures to fecal pathogens and public health risk. However, coliforms are not always a representative indicator of viral contamination (Skraber, Gassilloud, & Gantzer, 2004). Concentrations of fecal indicator bacteria are not correlated with human viral pathogen concentrations (Baggi, Demarta, & Peduzzi, 2001; Espinosa, Arias, Sánchez-Colón, & Mazari-Hiriart, 2009), and viruses can be more resistant to wastewater treatment than bacteria (Dias, Ebdon, & Taylor, 2018; Sinton, Hall, Lynch, & Davies-Colley, 2002). The US EPA and other regulatory boards are auditing coliphages for future use as indicators specific to viral contamination (US EPA Office of Water, 2015). Bacterial indicators may be especially problematic for assessing viral loads after UV disinfection because viruses often require higher UV dosage than coliform bacteria (Chang et al., 1985; Hijnen et al., 2006; Malley Jr. et al., 2004). Due to the importance of determining viral contamination independent of bacterial indicators, characterizing the viral levels of UVD unit effluent helps to gain a better understanding of risks to public health.

Viral indicators of fecal contamination include coliphages, defined as viruses that infect *E. coli*, although they may also infect other Gram negative bacteria. They are generally divided into two groups, somatic coliphages, which infect *E. coli* by attaching to receptors in the cell wall, an F-specific (F+) or male-specific coliphage, which infect *E. coli* via the sex pili encoded on the F plasmid (Jofre, Lucena, Blanch, & Muniesa, 2016). Four different F-specific serogroups have been documented, with serogroup I and IV isolated from animals, serogroup III from humans, and serogroup II primarily from humans, but also a small number of animal samples

(Grabow, 2001). F-specific coliphages can also be divided based on their nucleic acid composition into RNA (FRNA) coliphages, which have small, icosahedral capsids; rod-shaped, single-stranded DNA F⁺ coliphages; and icosahedral capsids with double-stranded DNA (Cole, Long, & Sobsey, 2003; Jofre et al., 2016; Mesquita et al., 2009).

The use of coliphages as viral indicators has become widespread among water quality researchers, and the US EPA has approved detection methods primarily for groundwater sampling, but also for wastewater analysis (US EPA Office of Water, 2015). Coliphages are considered appropriate indicators of human enteric viruses because of their similar morphology and resistance to environmental stressors as well as their low probability of replicating under environmental conditions (Jofre et al., 2016; US EPA Office of Water, 2015). Both somatic and F⁺ coliphages have been used as indicators of viral concentrations in wastewater or surface waters impacted by wastewater effluent (Ballester, Fontaine, & Margolin, 2005; D. Francy et al., 2011; Gomila, Solis, David, Ramon, & Lalucat, 2008; Lucena et al., 2004). Differences have been observed between the prevalence and persistence of F⁺ and somatic coliphages, but no conclusion has been reached as to which group is a better fecal indicator (Grabow, 2001; Lee & Sobsey, 2011).

Coliphages are effectively inactivated by ultraviolet irradiation, despite the need for relatively high UV doses. MS2 coliphages typically require 50 mJ/cm² for 2-log reduction (Clancy et al., 2002; Thurston-Enriquez et al., 2003), which is achieved when wastewater treatment plants are operating properly, as evidenced by somatic and F⁺ coliphage concentrations that are generally below or close to limits of detection in WWTP effluent (D. Francy et al., 2011; Rose et al., 2004). When coliphages are present in UV-treated effluent, the concentrations of FRNA coliphages have a higher correlation with enteric virus concentrations

than the correlation between fecal indicator bacteria and enteric viruses (Arie H Havelaar, Olphen, & Drost, 1993). The prevalence of coliphages in UVD unit effluent from onsite sewage systems has not been examined, although UVD units have reduced F+ coliphages by 5-log under simulated field conditions with spiked influent (Leverenz et al., 2006). With further characterization of coliphage levels in UVD unit effluent, additional insight will be gained into viral treatment by UV disinfection as well as the use of coliphages as viral indicators for onsite wastewater treatment.

Methods

To quantify the levels of F+ coliphages in effluent from UVD units, researchers initially analyzed wastewater samples using the single agar layer (SAL) method (US EPA Method 1602). However, very few of the samples contained F+ coliphages, and when they were present, they were difficult to detect due to low concentrations. Because of these difficulties, all further analysis of wastewater samples was completed with the two-step enrichment method (US EPA Method 1601). Previous monitoring of marine water fecal contamination has also transitioned from the SAL method to two-step enrichment, which provided a higher sensitivity for F+ coliphage detection, most likely due to the larger sample volume (Ballester et al., 2005). Although aliquots of the wastewater samples were used to try to determine the most probable number per 100 mL, most of the results were either negative for all aliquots or positive for all aliquots, so the results are reported qualitatively as negative or positive.

In preparation for the analysis, a stock culture of *E. coli* F_{amp} was prepared from previous stock culture and frozen in 20% glycerol at -70°C. A stock strain of FRNA coliphages was also cultured from previous stock culture in an *E. coli* F_{amp} host. The stock was frozen at -70°C in

20% glycerol at a concentration of approximately 10^7 PFU/100 mL. Other general reagents were prepared, including:

- 80X (4M) magnesium chloride solution: 814 g of magnesium chloride hexahydrate in final volume of 1L deionized water, autoclaved at 121°C and 15 psi for 15 minutes
- stock 1.5 mg/mL ampicillin/streptomycin solution: 0.15 g of ampicillin sodium salt and 0.15 g of streptomycin sulfate in 100 mL deionized water, filtered through a 0.22 μ m-pore-size membrane filter and stored at -20°C

Single Agar Layer (SAL) Procedure

Within 48 hours of sample collection, the single agar layer assessment for F+ coliphages was performed. A 100-mL wastewater sample was warmed to 35°C, at which point it was inoculated with 10 mL *E. coli* F_{amp} grown from a frozen concentrated culture by incubation in tryptic soy broth or nutrient broth for 10-18 hours. The sample was then warmed in a water bath to 43°C and added to 100 mL of 2X tryptic soy agar (autoclaved for 15 minutes at 121°C and 15 psi) with 0.5 mL of 80X magnesium chloride solution and 2 mL of 1.5 mg/mL Ampicillin/Streptomycin solution (for a final antibiotic concentration of 15 μ g/mL), also at 43°C. The mixture was gently swirled to ensure complete mixing, and was then poured into ten 100-mm diameter petri dishes (approximately 20 mL per dish). Once the agar was hardened, the plates were covered, inverted, and incubated at $36 \pm 1^\circ\text{C}$ for 16-24 hours. The concentration of F+ coliphages was determined by counting plaque forming units in the lawn of *E. coli*. Quality

control was ensured by using 50 mL of 1X phosphate-buffered saline (PBS) as a negative control, and inoculating 100 mL of PBS with approximately 60 plaque-forming units (PFU) of stock F+ coliphages for a positive control.

Two-Step Enrichment MPN Procedure

Sample volumes for the two-step enrichment procedure varied between 150 mL and 250 mL. The largest sample available was used to maximize the probability of detecting F+ coliphages. For samples from septic tanks, a 10-fold dilution of the original sample was analyzed. Samples were collected from the location of interest and stored at 4°C until analyzed.

Samples were enriched within 48 hours of sample collection. To enrich the wastewater sample for F+ coliphages, 1.25 mL of stock magnesium chloride solution, 5 mL of 10X tryptic soy broth, 1 mL of 1.5mg/mL Ampicillin/Streptomycin solution, and 0.5 mL of log-phase *E. coli* F_{amp} were added per 100 mL of the wastewater sample. The sample bottle was capped and inverted at least 5 times to mix. The sample was then aliquoted into five 30 mL portions, fifteen 10 mL portions, or ten 25 mL portions. These were incubated for 16-24 hours at 36 ± 1°C. The same procedure was performed with 100 mL of 1X PBS for a negative control and 100 mL of 1X PBS inoculated with approximately 60 PFU of stock F+ coliphages for a positive control.

After 16-24 hours, tryptic soy agar (autoclaved for 15 minutes at 121 °C and 15 psi) was cooled to 45°C and inoculated with 2 mL of log-phase *E. coli* F_{amp} and 1 mL of 1.5mg/mL Ampicillin/Streptomycin solution per 100 mL of agar. 100-mm diameter petri dishes were poured with agar and allowed to cool completely. (Note: When tryptic soy agar plates were prepared 24 hours beforehand and kept at 4°C until spotting, no zone of lysis was observed

around the positive control.) The enriched samples were then removed from the incubator and inverted at least 25 times. Approximately 5-8 μL of each portion of the enriched sample was spotted onto the plates. The plates were left right-side-up for 30-60 minutes to allow the spots to absorb into the agar. They were then inverted and incubated at $36 \pm 1^\circ\text{C}$ for 16-24 hours. After this period, the plates were examined for zones of lysis around the spots, indicating presence of F+ coliphages. The data were then used to calculate most probable numbers (MPN) for F+ coliphage concentrations in wastewater samples.

In some cases, the concentration of antibiotics was not sufficient to inhibit growth of bacteria present in the wastewater samples. Therefore, the Streptomycin/Ampicillin concentration was increased. Concentrations between 25 $\mu\text{g/mL}$ and 75 $\mu\text{g/mL}$ were used for post-UV and pump chamber samples, and concentrations between 15 $\mu\text{g/mL}$ and 150 $\mu\text{g/mL}$ were used for pre-UV and septic tank samples. For all antibiotic concentrations, positive controls exhibited zones of lysis.

Results

Twenty-one pump chamber samples were characterized for the presence of F+ coliphages (see Table 12). Five (24%) of the samples were positive for F+ coliphages. The range of most-probable number results for positive samples were between 3 and greater than 2500 MPN/100 mL. No F+ coliphages were observed in 6 samples from septic tanks preceding UVD units. No sample could be collected in the septic tanks preceding the UVD units where pump chamber samples were positive for F+ coliphage.

Table 12. Prevalence of F+ Coliphage in Pump Chamber Samples (n=21)

	F+ Negative	F+ Positive	Percent Positive
UVD Unit Functioning	7	2	28.6%

UVD Unit Not Functioning^a	6	3	33.3%
^a UVD unit classified as not functioning if the UV bulb was off or had a high biofilm deposit.			

Discussion

In our study sample, 3 of the samples with F+ coliphages were from UVD units classified as not functioning and 2 were from UVD units classified as functioning. However, upon further investigation, possible reasons for suboptimal disinfection were noted in all five of the OSSs with F+ coliphages. These reasons include a burnt-out UV bulb, high biofilm deposit on the protective sleeve, UV bulb burning faintly, and installation of a UV bulb that was not confirmed for germicidal efficacy. These results indicate that no or decreased UV disinfection may result in a higher prevalence of viruses in OSS effluent. Previous research has found UV disinfection units to be capable of a mean 5-log removal of MS2 coliphage, with final effluent concentrations below 10 PFU/100 mL (Leverenz et al., 2006). These findings support the conclusion that when the UVD units observed in the study were functioning optimally, F+ coliphages were reduced below 10 PFU/100 mL, but that UVD units not functioning properly had higher levels. However, additional research is needed to better evaluate viral inactivation in UVD units and the downstream effects on public health.

The low prevalence of F+ coliphages observed in this study corresponds with previous research findings. Samples from wastewater treatment facilities, where wastewater is combined from a large number of different sources, are almost always positive for F+ coliphages, with concentrations ranging from 10^2 – 10^8 PFU/liter (Cole et al., 2003; D. Francy et al., 2011; Schaper, Jofre, Uys, & Grabow, 2002). However, the prevalence of F+ coliphages is typically lower than 10% for individual human fecal samples and residential lift station samples (Calci,

Burkhardt, Watkins, & Rippey, 1998; Schaper et al., 2002). This indicates that although F+ coliphages may be a good indicator of combined wastewater contamination, its inconsistent prevalence in humans may lower its applicability as a viral indicator for wastewater generated by fewer individuals. Even lower prevalence of F+ coliphages can be expected after UV disinfection because coliphages are effectively inactivated by ultraviolet irradiation (Batch, Schulz, & Linden, 2004; Rose et al., 2004). Somatic coliphage are more prevalent in wastewater and human fecal samples, and may be a better indicator of viral levels for OSS effluent than male-specific coliphage (Dias et al., 2018; Grabow, Neubrech, Holtzhausen, & Jofre, 1995; A H Havelaar, Pot-Hogeboom, Furuse, Pot, & Hormann, 1990). Additionally, it is important to note that many of the studies comparing human viral load to coliphage concentrations sample environmental water (lakes, rivers, recreational areas), but their correlation in raw and secondary-treated sewage is less conclusive (Arie H Havelaar et al., 1993). Additional research should be conducted to evaluate different coliphage indicators for use in onsite sewage sampling.

HOMEOWNER FEEDBACK ABOUT UVD UNITS

Homeowner Questionnaire Results

237 owners of OSSs with UVD units responded to the questionnaire that accompanied the invitation to participate in this study. 178 (75%) respondents filled out the mailed questionnaire, 48 (20%) used the online response form, and 11 (5%) responded via phone.

The answers to the questionnaire provided information about the resources that are available to homeowners to better operate and maintain their UVD units, as well as the frequency of their personal UVD unit maintenance.

The first 3 questions asked whether the homeowner knew where their OSS was located or had access to the OSS record drawing and the UVD unit manual. All respondents knew where their OSS was located, 53% had access to a record drawing, and 23% had a manual from the UVD unit manufacturer (see Figure 4).

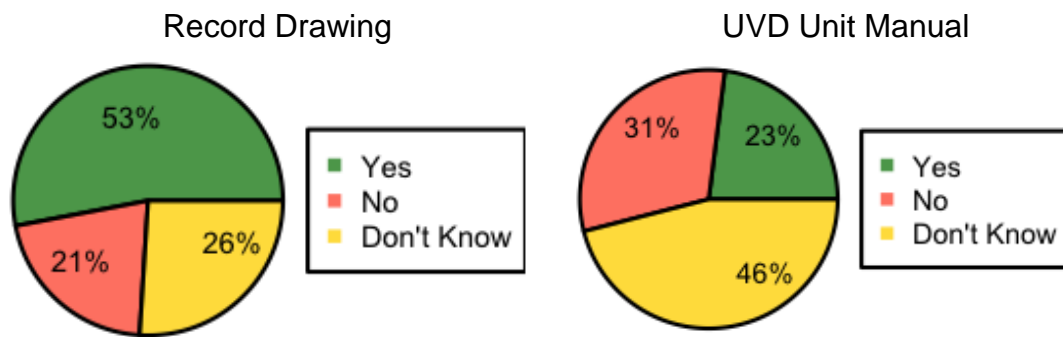


Figure 4. Proportion of Septic Owners Who Have Access to Record Drawings and Operation and Maintenance Manuals

The fourth question asked homeowners whose contact information they had to use if they were concerned with how their UVD unit was functioning. Most respondents indicated that they had the contact information for an operation and maintenance provider (82%), but a large

proportion also had contact information for the installer (19%), and the county health department (17%; see Table 13).

Table 13. Homeowners’ Access to Contact Information for Key Players in OSS Maintenance and Management

Contact Person	Homeowners Have Contact Information
Designer	9%
Installer	19%
O&M Provider	82%
County Health Department	17%
Department of Health	8%
None	4%

The questionnaire also asked respondents about their interest in topics related to their UVD units. Most homeowners wanted to receive additional information about how to prevent failures in their OSS (50%) and why they had a UVD unit (46%; see Table 14). Respondents also suggested additional topics of interest, including maintenance requirements, landscaping around the soil absorption area, septic tank additives, personal maintenance training, and potential waivers for installing and maintaining UVD units.

Table 14. Proportion of Homeowners Interested in Different OSS Topics

OSS Topic	% Homeowners Interested
OSS components	33
How to inspect OSS	38
What to put down drain	35
How to prevent failure	50
Why have UVD unit	46

The final question asked homeowners how frequently they inspected their own UVD units. Additional comments from homeowners revealed some confusion regarding which part of their OSS should be inspected to determine UVD unit functionality. Several residents listened for

the ATU blower, but did not check the UVD unit indicator light or alarm. Over half of the respondents (56%) did not inspect their UVD units, but relied on annual or semiannual inspections by service providers (see Figure 5).

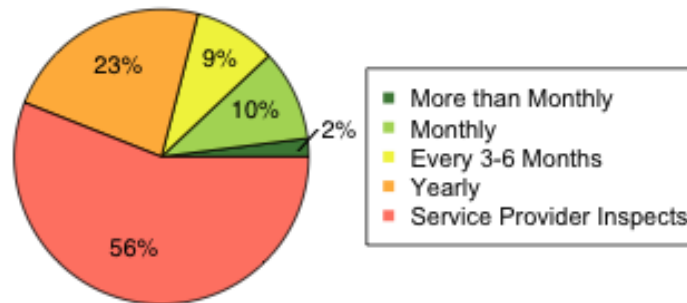


Figure 5. Frequency of Septic Owners Inspecting Their UVD Unit

It is important to note that this questionnaire surveyed homeowners, not residents of houses with UVD units. Renters or temporary residents may have less access to resources or a poorer understanding of the installed OSSs, even though their engagement in proper operation and maintenance is essential for optimal OSS performance. The responses may also be biased by the fact that all but 3 of the questionnaire respondents volunteered to participate in the study. The high interest in learning more about UVD units may not be representative of the county residents in general, but merely a factor of the interest of those who volunteered for the study.

The results from this questionnaire indicate that some residents of Pierce and Thurston County have information about UVD units and resources for good operation and maintenance. However, there is room for improvement to increase the proportion of UVD unit owners who have operation and maintenance manuals, know how to check whether their UVD units are working, and are more aware of the current functioning of their UVD units. The results also show that certified maintenance providers play an important role in communicating with homeowners and residents about UVD units and responding to maintenance and repair needs. A

survey in Snohomish County, Washington found similar results, and recommended working with maintenance providers to increase effectiveness of outreach to homeowners (Frenzl & Ball, 2011). Future collaboration between state and local public health agencies and maintenance providers could provide additional information to owners of UVD units. This would likely improve system operation and maintenance, resulting in improved performance.

Homeowner Feedback During Field Evaluations

Through conversations with homeowners during the study, researchers learned about their attitudes toward and perspectives about ultraviolet disinfection units. Many homeowners were interested in the study because they wanted to know whether their OSS was functioning properly. Because UVD units and their pretreatment sequences are often expensive to install, homeowners expressed concern over malfunctioning systems, OSSs that had recurring problems, and improper maintenance that did not ensure long-term sustainability of the UVD unit.

Most of the homeowners that participated in the study were interested in their on-site septic systems and ultraviolet disinfection units. They wanted to gain a better understanding of how the OSS was treating wastewater and wanted to know whether it was performing as designed. Many also expressed an understanding of the importance of on-site systems in general, and disinfection units specifically, in protecting water quality. To paraphrase a comment that was heard multiple times: “If this is what is available to keep the water safe, then it’s important that we have it and that it’s functioning properly.”

Many study participants explained that they had experienced reoccurring problems with their UVD units. These included alarms going off, the bulb needing to be frequently replaced, and electrical issues. Some UVD units had continual problems, even when a certified maintenance provider was regularly repairing the deficiencies. Homeowners wanted their system

to function properly, and they wanted service providers to perform the required maintenance to keep the unit functioning well.

Homeowners also expressed frustration with the expense of owning an OSS with a UVD unit. Some homeowners were not expecting the additional expense of regularly replacing the UV bulb. Homeowners insisted that if the system does not function properly in the field, they should not be required to pay so much to have it installed.

This feedback indicates that many homeowners are committed to ensuring that their OSSs and UVD units are functioning properly. They also want to have more information about how to do this and how their OSSs function. Opportunities should be sought to provide more education to homeowners about their UVD units, how to respond to common issues, and how to communicate with their service providers about how to best operate and maintain their system.

CERTIFIED MAINTENANCE PROVIDER PERSPECTIVE

In order to form a more complete understanding of UVD unit maintenance, the barriers to maintenance, and the perspectives of industry experts, interviews and focus groups were conducted with certified maintenance providers in Pierce and Thurston counties. An interview with an OSS installer and service provider who works primarily in Thurston County was conducted on April 20, 2017. The semi-structured interview was conducted in the field, so the provider explained UVD unit maintenance and responded to questions. Additionally, a focus group was conducted at the Tacoma-Pierce Pierce County Advisory Industry Group Meeting on October 25, 2017, where 3 maintenance providers, 1 installer, and several local and state agency members were present. The focus group had a more structured format and focused on 4 primary questions:

1. What are your most common experiences with UVD units?
2. When you service or install an OSS with a UVD unit, what do you usually do to the unit?
3. How can we improve the use of UVD units in Pierce County?
4. What are the best ways to communicate with installers and service providers about study results?

The insight provided by maintenance providers and installers was considered when developing recommendations for WADOH regulations and when translating research for workers in the OSS industry and owners of UVD units.

The underlying approach to UVD units seemed to differ between service providers in Thurston and Pierce counties. The provider interviewed in Thurston County understood UVD units to enable construction in areas that would otherwise be undeveloped. This provider

proactively minimized failures by replacing bulbs every two years and providing consistent cleaning. In contrast, providers in Pierce County questioned the usefulness of UVD units. Their perspective was that the fecal coliform reduction provided by the UVD unit may not be worth the high cost and length of time that is required to maintain UVD units. These underlying perspectives may explain some of the county-level differences in maintenance performed on UVD units.

During the interview and focus group, industry experts described several barriers to maintaining well-functioning UVD units. The three that were discussed in greatest detail were UVD unit design, homeowner disinterest, and poor installation. Maintenance providers in both Thurston and Pierce Counties explained that aspects of UVD unit design are limiting factors. The Teflon sleeve included in some unit models is difficult to clean without scratching or tearing it, and the limited protection against water intrusion into the UVD unit and the electrical housing is difficult to correct. Another important barrier to maintenance was poor installation. One maintenance provider pointed out that installers and maintenance providers do not know each other's expertise, which results in UVD installations that do not provide easy access for maintenance. Another key issue was lack of homeowner investment. Although providers in both Pierce and Thurston counties indicated that OSS owners were often unwilling to pay for replacement parts, this seemed to be more prevalent in Pierce County. OSS installers and maintenance providers attributed this to the lack of effluent sampling, which in Thurston County provides a quantitative indication that the UV bulb needs to be replaced, as well as a lack of environmental concern among Pierce County residents. In addition to these three major barriers to maintenance, other difficulties arise due to poor communication between regulators and

installers, the parts for old models no longer being sold, and a hesitation to maintain UVD units because of their fragile components.

Some of these barriers to maintenance were also observed during the field work for this study. Poor installation limited access to 15% of the studied UVD units, and many torn Teflon sleeves or cases of water intrusion were observed. Future management plans and regulations for UVD units should consider these issues and work with maintenance providers and installers to remove these barriers and enable optimal functioning of UVD units.

The insight that UVD unit installers and maintenance providers shared about maintaining units and interacting with homeowners was incorporated into research translation products. When designing presentations to workers in the OSS industry, presenters incorporated detailed information about poor installation and addressed the potential connection between inadequate maintenance and UVD unit malfunction. Additionally, reports to homeowners encouraged residents to talk with maintenance providers and gain a better understanding of the importance of UV disinfection. These efforts to communicate important information have hopefully increased the impact of the research study for a broader audience.

CONCLUSION

The aim of this research study was to determine the effectiveness of ultraviolet disinfection units installed in Western Washington. The results indicate that UVD units provide high-quality effluent when they are properly installed and maintained and their pretreatment is properly functioning. However, a high proportion of UV bulbs were not burning, which significantly increases the likelihood that the effluent discharged from these systems is not meeting treatment standards. The study also found that inadequate installation and maintenance, as well as county-level OSS management plans, are barriers to optimal UVD unit performance. Although these findings provide important insight, additional research should examine wastewater treatment at different locations throughout OSSs with UVD units and include more long-term aspects of OSS operation and maintenance to gain a more thorough understanding of how to optimize UVD unit performance.

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APPENDIX A. METHODS

Participant Recruitment and Selection

The target population for this study were all ultraviolet disinfection (UVD) units in Pierce and Thurston Counties, which were intended to provide a general idea of UVD unit performance throughout Western Washington. The many UVD units (over 2,000) in Pierce County have a variety of different treatment sequences and maintenance conditions and allowed for high participation rates, and the Thurston County UVD units (approximately 140) provide access to free-fall effluent samples, which were necessary to provide a more in-depth characterization of UVD unit effluent quality.

Researchers used results from a survey in Kitsap County to estimate the sample size necessary to determine the prevalence of UVD unit effluent exceeding Treatment Level A (200 CFU/100 mL) with a confidence interval of $\pm 10\%$ at a 90% confidence level. The predicted proportion of properly functioning UVD units was 56% in Pierce County (the proportion observed in Kitsap County) and 14% in Thurston County (a quarter of the proportion observed in Kitsap County). Researchers determined that these estimates were conservative and that the sample size they provided would be sufficient to answer the study aims. Using Formulas 1 and 2, the calculated target sample sizes were 65 in Pierce County and 27 in Thurston County.

$$SS = \frac{Z^2 * (p) * (1-p)}{C^2} \quad (1)$$

$$sample\ size = \frac{SS}{\left(\frac{SS-1}{Pop}\right)+1} \quad (2)$$

where:

Z = Z-score for the confidence level of interest, in this case 1.65 for 90% confidence level

p = predicted proportion of UVD units with effluent exceeding Treatment Level A standard

C = desired confidence interval

Pop = total number of units in the target population

In May 2017, Washington State Department of Health (WADOH) sent a letter to all owners of UVD units in Pierce and Thurston Counties, 2,034 and 141, respectively (See letter in Appendix B). The letter explained the research study and invited them to volunteer in exchange for a reimbursement of their next required maintenance fee (\$60-130). By the beginning of June, 210 volunteers had responded from Pierce County, and 19 from Thurston County. To recruit additional volunteers from Thurston County, an additional letter was sent to all owners in Thurston County whose mailing address did not match the property address with the UVD unit. Phone numbers were available for 63 Thurston County owners, so they were also recruited by phone call. In the end, 34 Thurston County homeowners volunteered.

Because the number of Pierce County volunteers exceeded the pre-determined sample size, 65 volunteers were randomly selected to participate in the study. Each volunteer was assigned a random number, which were sorted from lowest to highest, and the volunteers with the lowest numbers were chosen to participate.

A member of the research team contacted participants by phone or email to schedule a UVD unit evaluation. Some participants could not be contacted, so their units were removed from the study. Additional units were removed because the property was difficult to access. If these units were in Pierce County, the next UVD unit on the randomized list was added to the study sample. Researchers visited 99 properties, but 2 of these properties did not have UVD units installed. Therefore, the final sample size was 97 UVD units, 65 from Pierce County and 32 from Thurston County.

All studied UVD units were assigned a random ID to protect the personal information of the participants. Identifying information was recorded in a secure document, in which each

property was connected to its random ID. All other study records included only the random ID, and the results were not linked to individual properties in any way.

Questionnaire Design

The invitation letter included a questionnaire with 6 questions about the information that owners have regarding their UVD unit (see Appendix B). UVD owners could complete the questionnaire by mail, online, or via phone.

To develop the questionnaire, previous surveys about homeowner perceptions of OSS maintenance, OSS failures, and residential water use were reviewed (Clallam County Health and Human Services, 2014; Elway Research, Inc., 2008; McNulty & Lindbo, 2004; Sherman et al., 1994; U.S. Geological Survey, 2004). The questions from these surveys were compiled, and the questions that were most relevant to the study were selected and categorized. The four categories for the homeowner questionnaire were: 1) household wastewater characteristics; 2) homeowner awareness of UVD unit operation, maintenance, and environmental impact; 3) homeowner behaviors intended to optimize OSS performance; and 4) demographic information. Additional questions specific to the context of this study and the use of UVD units were added. A draft of the questionnaire was tested with 5 OSS owners to evaluate clarity and preciseness of questions. The questionnaire was adjusted based on testing feedback. To encourage participation in the study, the questionnaire was shortened from 27 questions to the 8 questions that provided the most relevant information for improving services to UVD unit owners.

Onsite Observations

Researchers evaluated 97 UVD units during June-August 2017. OSSs were inspected using a checklist with predetermined indicators of installation and performance issues (see Appendix C). The checklist included issues identified in previous studies and during

consultations with industry experts (Leverenz et al., 2006; Loomis et al., 2004). Researchers examined the OSS control panel, electrical connection to the UVD unit, UVD unit housing, and UV bulb with protective sleeves. The level of biofilm buildup on the protective sleeve was classified on a 4-level scale: None, Low, Medium, or High. Although researchers had planned to evaluate UVD unit alarms and solids accumulation in the UVD unit housing, these features could not be observed in most UVD units, and they were therefore removed from the evaluation.

Wastewater Sampling and Analysis

Wastewater samples were collected post-UVD unit with disinfection, post-UVD unit without disinfection, and in the pump chamber. At each location, three samples were collected for bacterial, viral, and physical quality analysis. Upon arrival at a study site, researchers first collected free-fall UVD unit effluent samples if they were accessible. The flowrate through the UVD unit was determined by measuring the time needed to fill a 100-mL bottle. The UVD unit was then turned off and the disinfected wastewater was flushed through the unit. Samples of non-disinfected wastewater were then collected. Researchers also sampled from the pump chamber, usually while the UVD unit was being flushed. The pump chamber samples were collected as close as possible to the end of the chamber in order to characterize the wastewater that would be discharged into the soil absorption system.

The physical quality of the wastewater samples was measured as soon as possible after collection (within 30 minutes). For a list of the measured parameters and the analytical method, see Table A.1.

Table A.1. Physical Wastewater Quality Parameters and Analytical Methods

Parameter	Analytical Method
Temperature	Standard Method 2550B
pH	Glass electrode Standard Method 4500 H ⁺
Dissolved Oxygen	Luminescent Method ASTM D888-09
Conductivity	Conductivity cell Standard Method 2510
Turbidity	EPA Standard Nephelometry Method 180.1
UV Transmittance	Spectrophotometry with portable meter

Physical wastewater quality meters were calibrated before each day of sampling, and for 10% of the post-UVD unit samples, duplicate samples were analyzed. Duplicate values were similar for all measurements except turbidity. The turbidity meter was determined to be imprecise, as it did not produce stabilized readings. To maximize precision, researchers repeated the turbidity measurements for each sample until two successive measurements were similar to each other. However, this did not correct for all of the imprecision introduced by the meter, so turbidity measurements should be interpreted as estimates of the true turbidity and are reported with only one significant figure. The measurements were determined to be unbiased because correct turbidity values of calibration solutions were measured before and after sampling.

Samples for microbiological analysis were stored in a cooler with ice at 4 °C until delivered at the laboratory. Thurston County Environmental Health Water Laboratory performed Thermotolerant (Fecal) Coliform Membrane Filtration, Standard Method 9222 D (D. S. Francy & Darner, 2012). All samples were analyzed within 8 hours of collection. Accurate analysis was ensured by using *Escherichia coli* for a positive control and *Enterobacter aerogenes* for a negative control. One duplicate sample was run each day to ensure consistency and accuracy. Samples were analyzed for male-specific coliphage at the Environmental and Occupational Health Microbiology Laboratory at University of Washington. Analysis was initially performed

using the single agar layer (SAL) procedure (US EPA Method 1602).). However, due to the low concentrations of F+ coliphages, analysis was continued with the two-step enrichment method (EPA Method 1601).

Review of Maintenance Records

Data about OSS characteristics and maintenance inspections were compiled from lists provided by local health jurisdictions and review of publicly available service reports. TPCHD provided a list on 4/3/17 that included information for all advanced treatment systems in Pierce County. The list included system components, as-built date, number of bedrooms in the household, date and company of last service inspection, date of last UV bulb cleaning, date of last UV bulb replacement, and date of last OSS pumping. The OSSs on the original list provided by TPCHD of UVD units were extracted from this larger list. TCPHSS provided a list on 5/24/17, which included the information listed above as well as the status of the operational permit certificate and the contracted maintenance provider, the amount of scum and sludge in the pretreatment tank at the last inspection, the size of the pretreatment tank, and the required treatment level. Using the service reports publicly available on OnlineRME, all dates after 4/3/17 were adjusted to the most recent date preceding 4/3/17 to correspond with the timing of the list from TPCHD. All dates before 2010 were removed from both lists to create a consistent reporting timeframe. The data for both counties was combined using Microsoft Excel.

For OSSs evaluated in this study, the inspection, cleaning, pumping, and bulb replacement dates were updated to reflect the most recent occurrences before the study's onsite evaluation. This information was added by reviewing service reports. This information was then combined with data from field evaluations based on parcel ID. The accuracy of the data combinations was checked by ensuring that the information for 10% of the evaluated systems

was the same in all initial datasets and in the final dataset. Any dataset that contained both identifying information and study results was password protected to ensure participant confidentiality.

Creating Dataset of Thurston County Retrospective Quarterly Compliance Results

Data from all fecal coliform samples from UVD units in Thurston County are recorded in the OnlineRME database. A code was written using Python's Selenium and Tabula modules to extract all PDFs on the pages for all 141 UVD units on the list provided by TCPHSS as well as 2 additional properties identified by maintenance providers (total of 143 properties). The sampling date, location, type, and result were extracted from sampling reports. The inspection date, type, and comments, as well as information about whether the UV bulb was on and whether the bulb had been cleaned, was extracted from service inspection reports. Due to anomalies in the reporting, sampling results and inspection comments were extracted manually for 12 of the UVD units.

After data extraction from the online portal, the problems noted during service inspections were coded into 2 categories: deficiency with the UV bulb and/or deficiency with a different part of the OSS. Deficiencies with the UV bulb included the bulb being off or the OSS flow bypassing the UVD unit. Examples of other deficiencies in the OSS include aerator malfunction, overdue pumping, and lack of electrical power to the OSS. The deficiency information from the most recent service inspection was then attributed to each sampling result. When multiple samples were collected between two inspections, the deficiency information was only attributed to both samples if it was the same before and after the samples were collected. This assumes that the OSS status would not change between two inspections if the inspections indicated the same status. In some cases, sampling did not take place at the same time as the

inspection, and the following inspection indicated a different deficiency status than the inspection preceding the sampling event. In these cases, if the sample was collected within 30 days of the most recent inspection (n=8), the OSS status at the time of that inspection was attributed to the sampling event. If the sample was collected more than 30 days after the most recent inspection, no deficiency information was attributed to that sampling event (n=13). Removing this information from the dataset did not impact the analysis estimates, nor their statistical significance. Deficiency coding minimized misclassification as much as possible, but some nondifferential misclassification is likely present due to time lags between sampling and inspections and incomplete reporting of OSS repairs.

To ensure data accuracy, the information for 10% of the sampling events in the final dataset was compared to the original dataset with separate information for inspection and sampling events.

Statistical Analysis

All data collected during the study was imported into R, and data analysis was conducted in R Studio (version 1.1.414) and Oracle Crystal Ball.

For analysis purposes, all fecal coliform measurements below the limit of detection were assigned a value of one whole unit below the limit of detection. If the limit of detection was 1, the measurement was assigned a value of 1. If the measurement was above the limit of detection, it was assigned a value of one whole unit above the limit of detection. This method was used in accordance with recommendations from the National Shellfish Sanitation Program (FDA, 2015). Fecal coliform concentrations were \log_{10} -transformed according to standard practice. Although the fecal coliform concentrations did not fit a log-Normal distribution, this fit was closer than the

fit to a Normal distribution. Log₁₀-transformed fecal coliform concentrations were used for all data analysis unless otherwise noted.

Analysis of Wastewater Samples Collected During Field Evaluations

Sampling data was initially evaluated with descriptive statistics and graphical representations. The fecal coliform levels were compared to Treatment Level and Action Level standards used in Washington State.

Fecal Coliform Reduction in UVD Units

The difference in the distributions of fecal coliform concentrations with and without UV disinfection was compared using a Wilcoxon rank sum test (or Mann-Whitney U test) because these values were not Normally distributed. The fecal coliform log-reduction by UV disinfection was calculated by subtracting post-UV fecal coliform concentrations from their paired measurements without UV disinfection.

Correlations between Fecal Coliform and Physical Wastewater Quality Parameters

Upon review of histograms, researchers determined that the fecal coliform data were not log-normally distributed, and many of the wastewater quality parameters were not Normally or log-normally distributed either. The Spearman's rank correlation was selected as a non-parametric correlation statistic that can be used for continuous data. The results from the Spearman's rank correlations between fecal coliform concentrations and the physical wastewater quality parameters were compared to scatterplots and Kendall's tau-B correlations, which correct for ties in the data. Each of these analyses yielded similar results.

Descriptive Analysis of Pump Chamber Fecal Coliform Results

One pump chamber result was classified as an outlier and removed from analysis because it was collected in a small tank that had filled with effluent from the UVD unit after it had been

turned off. The pump chamber fecal coliform results were neither Normally nor log-Normally distributed. Additionally, 18 of the 50 measurements were below the limit of detection.

Therefore, associations between pump chamber results and UV bulb malfunction were not examined with regression models. 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 from units where the bulb was properly functioning.

The correlation between pump chamber and post-UV fecal coliform concentrations was examined using Kendall's tau-B correlations. This correlation statistic, which includes a correction for ties, was selected as the most appropriate because of the high proportion of fecal coliform measurements that were below the limit of detection in both post-UVD and pump chamber samples.

Analysis of Retrospective Compliance Fecal Coliform Measurements

Associations between UV Bulb Malfunction and Fecal Coliform Results from Historical Sampling Reports

A Tobit regression model was run to assess the difference in geometric mean fecal coliform levels in UVD unit effluent divided by UV bulb status. Fecal coliform results were \log_{10} -transformed after adding 1 to each value due to the presence of 0s in the data (non-detects). The outcome variable in the model was fecal coliform concentration and the primary predictor variable was UV bulb deficiency. The model also adjusted for other OSS deficiencies and used robust standard errors clustered by property ID to account for any autocorrelation between samples from the same OSS. Censoring in the outcome variable was accounted for by using a

survival indicator in the Tobit model. The final model (see Formula 3) predicted the relative difference in geometric mean fecal coliform levels of the underlying uncensored measurements. Although 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.

$$Y_i^* = \beta_0 + \beta_1 * UV\ deficiency_i + \beta_2 * other\ deficiency_i + \varepsilon_i, \quad (3)$$

where:

Y_{ij}^* := Log Fecal coliform for observation i at site j

X_{ij} := Covariates for observation i at site j (include *UV deficiency*, *other deficiency*, *age*, and *sampling location*)

$\varepsilon_{ij} \sim N(0, \Sigma)$:= Error term clustered at the OSS level to account for inter-OSS interdependence

We modeled Y_i^* , the latent variable underlying the observed log fecal coliform concentrations, which are:

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

Two additional subgroup Tobit regression models were run for sensitivity analysis. The first model examined the effect of age on fecal coliform levels among UVD units with an operational UV bulb. The Tobit regression model was:

$$Y_i^* = \beta_0 + \beta_1 * \log(age + 1) + \beta_2 * other\ deficiency_i + \varepsilon_i \quad (4)$$

The second subgroup analysis examined only those UVD units observed during field evaluations and adjusted for access to a post-UVD unit sampling port. Tobit regression models with and without this adjustment were run, and the results were compared. The model with the adjustment included was:

$$Y_i^* = \beta_0 + \beta_1 * UV\ deficiency_i + \beta_2 * other\ deficiency_i + \beta_3 * sampling\ location_i + \varepsilon_i \quad (5)$$

In addition to evaluating the effect of UV bulb status on fecal coliform concentrations, the effect on UV bulb status on the exceedance of each site's individual Action Level was examined using a logistic regression model (see Formula 6). Due to laboratory technique, researchers could not determine whether the fecal coliform levels were exceeding the Action Level when the sample exceeded an upper limit of detection that was below the Action Level. These samples were excluded from the final model as missing data.

$$\text{logit}(FC\ exceeding\ AL_i) = \beta_0 + \beta_1 * UV\ deficiency_i + \beta_2 * other\ deficiency_i \quad (6)$$

Analysis of Current UVD Unit Status from Field Evaluations

Prevalence of Installation, Maintenance, and Current Physical and Electrical Issues

The prevalence of the issues observed during site evaluations was calculated for each individual county and both counties combined. The number of issues was divided by the total number of OSSs for which that issue could be observed. For example, the UV bulb and protective unit could not be observed at some sites, so the number of UV bulbs that were malfunctioning was divided by the number of UV bulbs where the light could be seen. Using the Pearson's Chi-square test of proportions, a 95% confidence interval was calculated around the observed proportions of each issue.

Associations between UV Bulb Malfunction and Other Indicators of Suboptimal

Performance

Effluent fecal coliform concentrations and UV bulb malfunction were the primary outcomes of interest for this study. Because of the small number of fecal coliform samples, it was not possible to determine the association between fecal coliform and other OSS issues.

Associations between UV bulb malfunction and the other observed issues in UVD unit

installation, maintenance, and current performance were examined to evaluate possible risk factors for bulb malfunction. Associations between the bulb malfunction and the other observed issues were examined in isolation and combined with other predictors of interest to adjust for confounding.

Fisher's exact tests of equal proportions were conducted for all binary variables. The Fisher's exact test was selected because two-by-two tables for all variables except 3 contained a cell with a value of 5 or less. The Fisher's exact test odds ratios for the three variables with no cells under 5 (insufficient cable slack, more than 2 years since bulb replacement, and more than 1 year since bulb cleaned) were compared with the results of a Chi-square test with Yates correction. The results were similar, so Fisher's exact test results were used for comparisons.

Non-binary predictor variables were standardized for comparison to binary variables by dividing each result by two times the standard deviation (Gelman, 2008). A simple logistic regression with robust standard errors was run with the unstandardized and standardized variables as predictors and UV bulb malfunction as the outcome variable.

To examine the effect of all predictors combined on UV bulb malfunction, an L1 regularized logistic regression model (also known as lasso regression) was run. Cross validation was used to determine the lambda correction factor that would create a model with the smallest mean-squared error and the model with the mean-squared error within one standard error of the minimum (Hastie & Qian, 2016; Krstajic et al., 2014). 18 observed indicators of suboptimal performance were included as predictors in the model, and any non-binary predictors were standardized for comparison with binary predictors (see Table A.2.).

Table A.2. Variables Used as Predictors in L1 Regularized Model

UVD unit on a non-dedicated circuit
Power switch for UVD unit inaccessible
Electrical connection to UVD unit unprotected
Electrical corrosion or damage
Inadequate cable slack
Cracks in UVD unit housing
UVD unit unprotected from flooding and debris
Leaking UV bulb protective sleeve
Level of biofilm deposit on UV bulb protective sleeve
Location of UVD unit
UVD unit make
ATU make
Age of OSS
Number of bedrooms served by OSS
Months since last OSS inspection
Months since UVD unit last cleaned
Months since UV bulb last replaced
Months since OSS last pumped

APPENDIX B. LETTER OF INVITATION TO PARTICIPATE IN STUDY



DEPARTMENT OF ENVIRONMENTAL & OCCUPATIONAL HEALTH SCIENCES
UNIVERSITY of WASHINGTON · SCHOOL OF PUBLIC HEALTH



April 2017

Dear On-site Sewage System Owner,

Research study opportunity

The University of Washington Department of Environmental & Occupational Health Sciences (UW) and the Washington State Department of Health (DOH) invite you to join a **research study** of septic systems with ultraviolet disinfection in Pierce and Thurston Counties. The study goals are to assess how well ultraviolet disinfection units work in the field and to identify ways to improve their performance throughout Washington.

Research study details

Participation in this study is **free and voluntary**. If you take part in the study, you will be asked to:

1. Allow us to observe your ultraviolet disinfection unit in operation and, where possible in Thurston County, collect wastewater samples. A UW Research Assistant will perform this assessment with the oversight of a DOH on-site septic system field specialist. The researcher will call you to schedule an assessment at a time that is convenient for you. You do not need to be present for the assessment.
2. Complete the attached consent form and answer the questions about access to septic system information and your maintenance practices. This should take less than 5 minutes.

As a thank you for your participation, we will **reimburse your fee to the local health department** for your next routine septic system O&M inspection.

How will the results be reported?

The individual results from this study will be treated as **confidential**. State and local health departments will not access individual results. The final report for this study will use combined data to produce a summary of findings; we will not report individual system or property owner surveys. Likewise, we will not map individual results. After the study verification period has been completed, the UW research team will delete any identifying survey data.

Note: DOH will **not** be enforcing compliance issues during these visits. However, we do have an obligation to report an obvious, public health threat (such as direct discharge of sewage) to both you and the local health department.

Can I get a copy of the study findings?

At your request, DOH will send you a copy of, or provide you a website address for, the study's final report. Additionally, at your request, UW will send you a copy of your individual system's assessment results.

How do I sign up?

Please start participating in our study by **completing and returning the attached consent form by May 19, 2017. A copy is provided for your records. This can also be completed online at: <https://is.gd/UVsurvey>**. NOTE: All volunteered septic systems may not be included in the study.

Contact information if you have questions

- In general, Randy Freeby, DOH, (360) 236-3379;
- Specific to Pierce County, Gary Porter at (253) 798-6569;
- Specific to Thurston County, Steve Petersen at (360) 867-2627; or
- Meagan Jackson, UW Graduate Research Assistant at meaganja@uw.edu

Thank you for your consideration!

Consent Form

As owner of the property shown below, I volunteer to participate in the On-site Septic System Ultraviolet Disinfection study performed by The University of Washington Department of Environmental and Occupational Health Sciences (UW) and Washington State Department of Health (DOH).

I understand that my participation is voluntary and that I can leave the study at any time. I understand that all volunteers may not be included in the study.

I understand that as a part of this study:

- A researcher will contact me to schedule an ultraviolet disinfection unit assessment. Assessments can be scheduled 9:00 AM-4:00 PM, Monday through Friday (in Thurston County, Monday through Wednesday only);
- I will allow researchers to enter my property at the agreed time to examine my ultraviolet disinfection system;
- I will allow researchers to take wastewater samples from my ultraviolet disinfection system (as applicable);
- I will tell the resident of the property about the scheduled assessment if I do not live there;
- I will answer the attached questions; and
- I will receive a reimbursement of the fee I pay to the local health department for an upcoming maintenance inspection.

I understand that the results of this study will be confidential. I understand that UW and DOH will not take any enforcement action. I understand that study reports and archived results will not include my personal information.

Select from the following:

I agree to participate in this study and allow the researchers to enter my property:

- at the agreed time; I need to be present
- at the agreed time; I do not need to be present

I own the property shown below and I:

- Am the current resident
- Am not the current resident

I would like a mailed or emailed (circle one) copy of:

- the study report
- the assessment results from my ultraviolet disinfection system

I, _____, have read the above information and volunteer to join this study. (Please print owner name above.)

Owner Signature

Date

Property Address

City

Zip-code

(____) _____ - _____
Daytime Phone Number

Email address (if prefer email)

Mailing Address (If different than above)

City

State

Zip-code

Please answer the following questions about septic system information and maintenance:

1. Do you know where your septic system is located?

- Yes
- No

2. Do you have a copy of the drawing ("as-built") showing the location of your septic system?

- Yes
- No
- Don't know

3. Do you have a copy of an operation and maintenance manual from the manufacturers of your ultraviolet unit?

- Yes
- No
- Don't know

4. Whose contact information do you have to use if you are concerned about how your system is functioning? Select all that apply.

- System designer and manufacturer
- System installer
- Operation and maintenance service provider
- County health department
- Washington State Department of Health
- Other (Please specify): _____
- I do not have septic system contact information

5. Which septic system topics would you like more information about? Select all that apply.

- The parts of my septic system and what they do
- How to inspect my septic system
- What (and how much) is ok to put down the drain
- How to prevent future failures in my system
- Why I have an ultraviolet unit
- Other (Please specify): _____

6. How often do you personally make sure that your septic system is working?

This may include checking the water levels in the tanks, inspecting the drainfield for surfacing wastewater, checking to make sure that the ultraviolet unit and pump are running, or other activities.

- Monthly
- Every 3-6 months
- Yearly
- I let my service provider take care of this
- Don't know

Gender: Male Female Prefer not to answer

Age: _____ Prefer not to answer

Thank you for your participation!

APPENDIX C. UVD UNIT FIELD INSPECTION CHECKLIST

Random ID #: _____

Evaluation completed by: _____

Evaluation completed on: Date: ____ / ____ / ____ Time: _____

- | | | | | |
|----|---|------|----|-----|
| 1. | Control panel: | N.A. | | |
| | a. Power On/Off Switch Accessible | Yes | No | |
| | b. Is enclosure watertight. | Yes | No | |
| | c. Alarm present | Yes | No | |
| | If present, operating properly. | Yes | No | |
| | d. UV unit on an independent circuit breaker | Yes | No | |
| 2. | Power supply to UV unit | | | |
| | a. Protected from elect. power disconnection | Yes | No | |
| | b. UV lamp 'ON'. | Yes | No | |
| | c. LED indicator present | Yes | No | |
| | LED indicator easily visible | Yes | No | N/A |
| | d. Splice box lid and cord grips are tight. | Yes | No | |
| | e. Power cord length from ballast in panel to UV lamp ≤ 50 ft | Yes | No | N/A |
| | f. Adequate cable slack present to UV lamp | Yes | No | |
| | g. Electrical system is free of corrosion/damage. | Yes | No | |
| 3. | UV housing unit: | | | |
| | a. Location ____Buried ____Within a tank ____Other:_____ | | | |
| | b. Protected from freezing, flooding, debris, damage | Yes | No | |
| | c. Unit accessible for cleaning and maintenance | Yes | No | |
| | d. Appears in good condition. | Yes | No | |
| | e. Leaks/Cracks present. | Yes | No | |
| 4. | UV Contact chamber, lamp, and sleeve conditions | | | |
| | a. Evidence of damage or leakage. | Yes | No | |
| | b. UV lamp completely enclosed in the protective sleeve | Yes | No | |
| | c. Sludge buildup at bottom of contact chamber. | Yes | No | |
| | d. Type of protective sleeve: __ Quartz __ Teflon __ Other: | | | |
| | e. Biofilm buildup on protective sleeve. None__ Low __ Medium__ High__ | | | |
| 5. | Accessibility for field monitoring and sampling | | | |
| | a. Accessible location to obtain representative effluent sample. | Yes | No | |
| | b. Fecal coliform samples collected for analyses. | Yes | No | |
| | c. Flow measurement taken. | Yes | No | |

NOTES

APPENDIX D. REPRESENTATIVENESS OF STUDY SAMPLE

The study sample included 22% of all UVD units in Thurston County and 3% of all UVD units in Pierce County. To determine whether the sample was representative of the target population, the age of OSS, make of ATU and UVD unit, and recent maintenance were compared between the study sample and all OSSs with UVD units in Pierce and Thurston County. Descriptive statistics were calculated for all continuous variables, and prevalence was determined for categorical variables (see Table D.1). These were compared qualitatively as well as with statistical inferential analysis. For continuous variables, the mean in the study sample was compared to the mean in the target population using a two-sided, one-sample t-test with unequal variance. Prevalence was compared with a one-sample chi-squared proportions test. Although some of the continuous variables were not Normally distributed in the study sample, a non-parametric comparison would be more conservative than the parametric t-test, and the Bonferroni correction compensates for the anticonservative nature of the t-test. Results from these tests are given in Table D2.

Based on this analysis, the age and models of the study sample are a good representation of all UVD units in the target population. However, the study sample has, on average, been maintained more recently than the target population. This is especially true for the time since the most recent UV bulb cleaning, as the study sample has a statistically significant different mean time since bulb cleaning compared to the target population. Another statistically significant difference is in the proportion of UVD units in Thurston County that do not have an operational permit certificate (see Table D.2). Because of these differences, the study may underestimate the prevalence of UVD unit issues, especially those related to biofilm buildup, in the target population.

Table D1. Characteristics of Sampled and Studied OSSs in Comparison with All OSSs in Pierce and Thurston Counties

	Thurston		Pierce				All Studied (n=99, 5%)	All (n=2,176)
	Studied (n=32, 23%)	All (n=142)	Studied (n=67, 3.3%)	Volunteered (n=210, 10%)	All (n=2,034)			
Age of OSS [years] ^a	12.0 ± 5.6 (1-24) NA=0	12.6 ± 6.0 (1-31) NA=1	10.6 ± 4.5 (2-20) NA=6	11.7 ± 4.6 (1-28) NA=16	11.2 ± 4.1 (0-29) NA=128	11.1 ± 4.9 (1-24) NA=6	11.3 ± 4.3 (0-31) NA=129	
Ultraviolet Disinfection Unit Makes^b								
Salcor 3G	9 (28%)	64 (45%)	22 (33%)	74 (35%)	776 (38%)	31 (31%)	840 (39%)	
The Disinfecter	23 (72%)	70 (49%)	38 (57%)	121 (58%)	1,078 (53%)	61 (62%)	1,148 (53%)	
Other	0	2 (1%)	4 (6%)	6 (3%)	38 (2%)	4 (4%)	40 (2%)	
No UVD Make Indicated	0	6 (5%)	3 (4%)	9 (4%)	142 (7%)	3 (3%)	148 (7%)	
Aerobic Treatment Unit Makes^b								
Bio-Microbics	18 (56%)	79 (56%)	34 (51%)	105 (50%)	955 (47%)	52 (53%)	1,034 (48%)	
Delta Environmental (Whitewater)	8 (25%)	26 (18%)	25 (37%)	90 (43%)	896 (44%)	33 (33%)	922 (42%)	
Other	6 (19%)	37 (26%)	6 (9%)	13 (6%)	131 (6%)	12 (12%)	168 (8%)	
No ATU Make Indicated	0	0	2 (3%)	2 (1%)	52 (3%)	2 (2%)	52 (2%)	
Maintenance History								
Time since last inspection [months] ^c	4.0 (4.4 ± 4.5, 0.2-18) NA=1	4.1 (7.1 ± 12, 0.1-76) NA=13	7.5 (6.7 ± 3.6, 0.4-13) NA=0	6.8 (6.5 ± 3.8, 0.3-17) NA=0	6.5 (6.8 ± 4.5, 0.1-35) NA=35	5.4 (6.0 ± 4.1, 0.2-18) NA=1	6.3 (6.8 ± 5.2, 0.1-76) NA=48	
Time since last UV bulb replacement [months] ^c	16 (25 ± 16, 13-65) NA=12	17 (24 ± 15, 4-90) NA=52	31 (32 ± 23, 1.6-80) NA=24	32 (34 ± 23, 0.4-80) NA=77	31 (32 ± 21, 0.2-81) NA=781	25 (30 ± 21, 2-80) NA=36	30 (32 ± 21, 0.2-90) NA=833	
Time since last UV bulb cleaning [months] ^c	4.1 (5.4 ± 5.4, 0.2-18) NA=2	4.1 (7.8 ± 11, 0.1-76) NA=23	9.9 (16 ± 19, 0.3-78) NA=3	8.6 (16 ± 19, 0.3-78) NA=16	9.3 (18 ± 21, 0.1-82) NA=235	7.4 (13 ± 17, 0.2-78) NA=5	8.9 (17 ± 20, 0.1-82) NA=258	
Last inspection included cleaning ^d	20 (67%) NA=2	78 (66%) NA=23	28 (44%) NA=3	101 (52%) NA=16	873 (49%) NA=235	48 (51%) NA=5	973 (50%) NA=258	
Operational Permit Status^b								
Issued	6 (19%)	33 (23%)						
In Review	13 (41%)	76 (54%)						
In Violation	13 (41%)	30 (21%)						
No Status Indicated	0	3 (2%)						

^aDescriptive statistics include mean ± SD (min-max)

^{b,d}Descriptive statistics include count and %

^cDescriptive statistics include median (min ± SD, min-max)

Table D.2. P-values of t-tests and chi-squared proportions tests to determine representativeness of studied OSSs

	All Studied (n=99)	All (n=2,176)	T-test p-value	Chi² test p-value
Age of OSS [years] ^a	11.1 ± 4.9 (1-24) NA=6	11.3 ± 4.3 (0-31) NA=129	0.593	
<i>Maintenance History</i>				
Time since last inspection [months] ^b	5.8 (4.1, 0.3-20) NA=1	6.3 (8.0, 0.1-152) NA=43	0.053	
Time since last UV bulb replacement [months] ^b	25 (21, 1-80) NA=36	30 (21, 0.2-92) NA=833	0.524	
Time since last UV bulb cleaning [months] ^b	6.3 (17, 0.3-78) NA=5	8.9 (20, 0.1-99) NA=257	0.013	
Last inspection included cleaning ^c	48 (51%) NA=5	903 (50%) NA=258		0.842
<i>Ultraviolet Disinfection Unit Makes^c</i>				
Salcor 3G	31 (31%)	840 (39%)		0.166
The Disinfector	61 (62%)	1,148 (53%)		0.096
Other	4 (4%)	40 (2%)		0.209
NA	3 (3%)	148 (7%)		0.197
<i>Aerobic Treatment Unit Makes^c</i>				
Bio-Microbics	52 (53%)	1,034 (48%)		0.370
Delta Environmental (Whitewater)	33 (33%)	922 (42%)		0.086
Other	12 (12%)	168 (8%)		0.147
NA	2 (2%)	52 (2%)		1.00
<i>Operational Permit Status^c</i>				
Issued	6 (19%)	33 (23%)		0.711
In Review	13 (41%)	76 (54%)		0.214
In Violation	13 (41%)	30 (21%)		0.012
NA	0	3 (2%)		0.833
^a Descriptive statistics include mean ± SD (min-max)				
^b Descriptive statistics include median (SD, min-max)				
^c Descriptive statistics include count and %				

APPENDIX E. GRAPHS AND TABLES TO SUPPLEMENT DATA ANALYSIS

Figure E.1. Histograms of Non-transformed and log-Transformed Fecal Coliform Concentrations in Samples from Post-UVD Unit, Post-UVD Unit Without UV Disinfection, and Pump Chamber

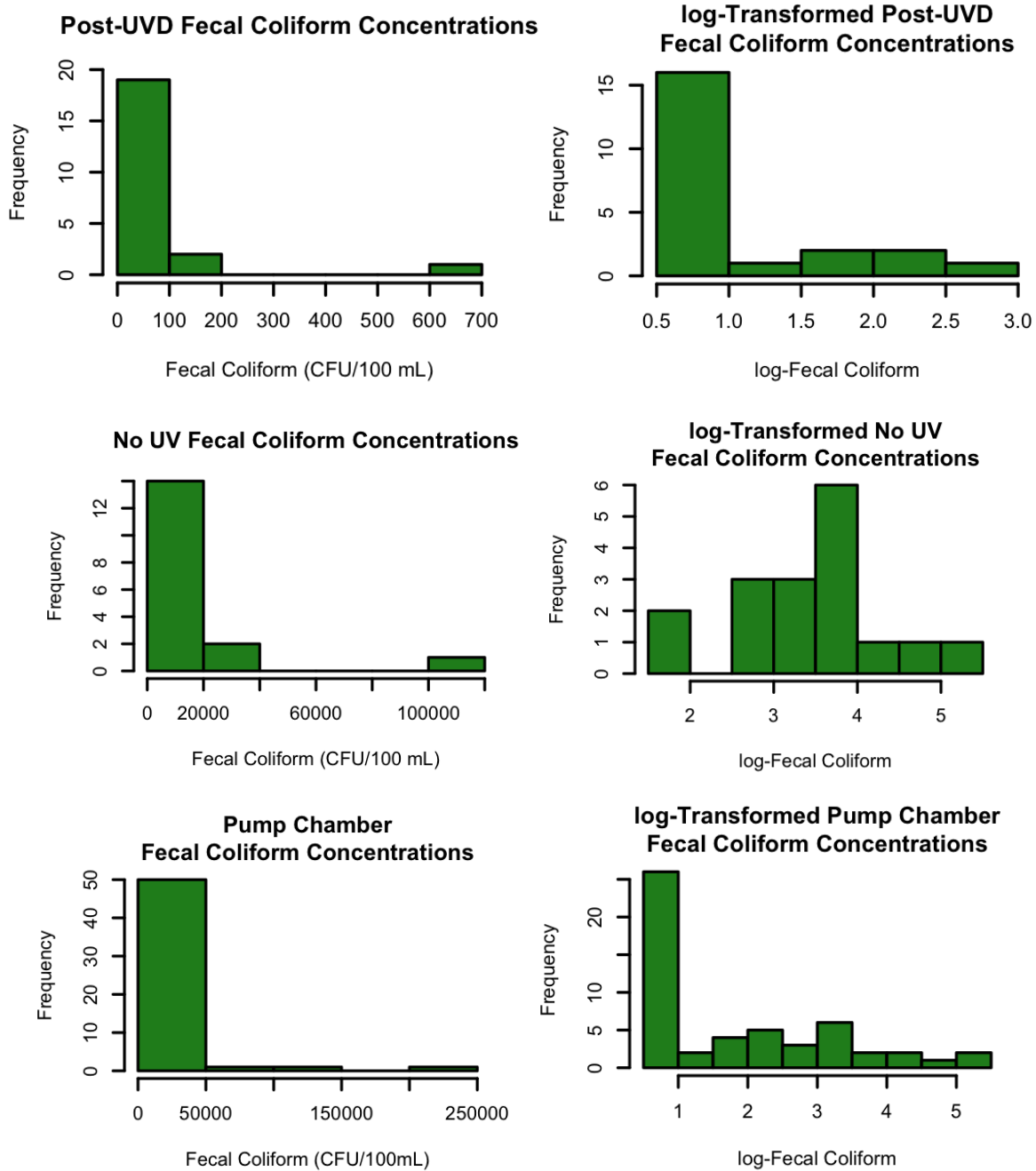


Figure E.2 Histogram of log-Transformed Fecal Coliform Concentrations from Retrospective Quarterly Compliance Samples

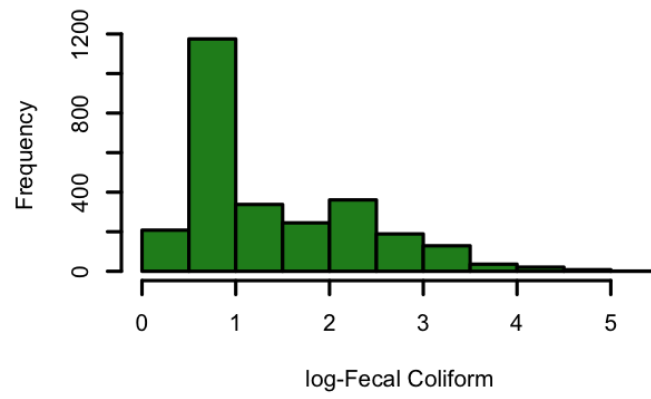
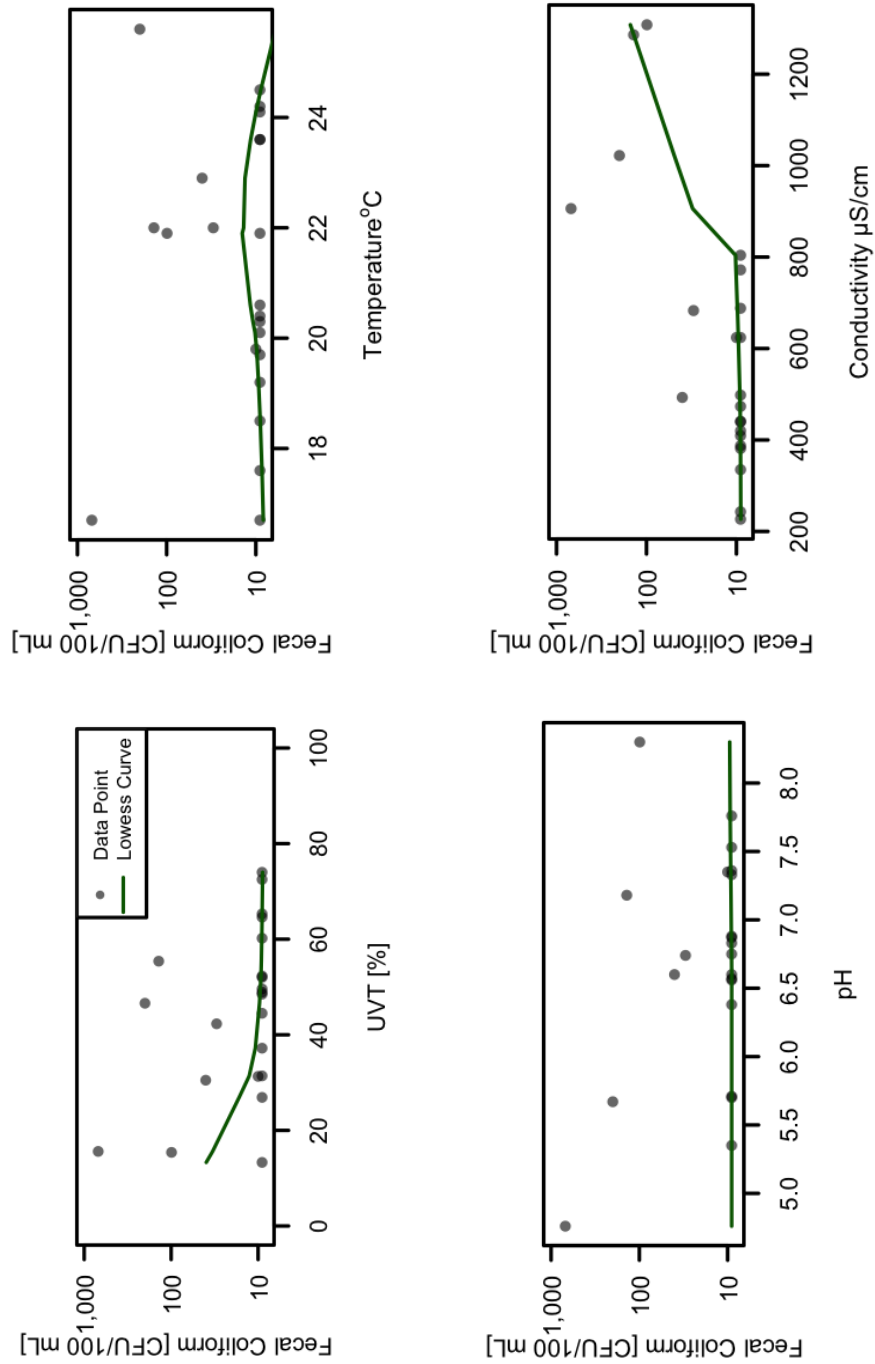
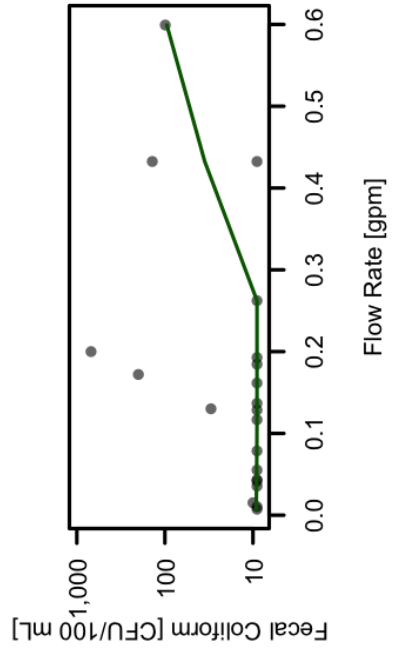
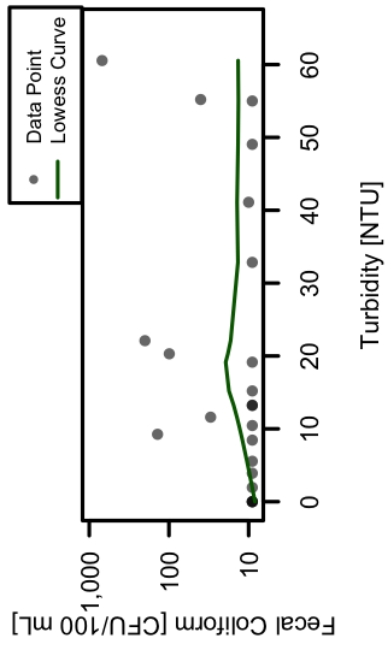
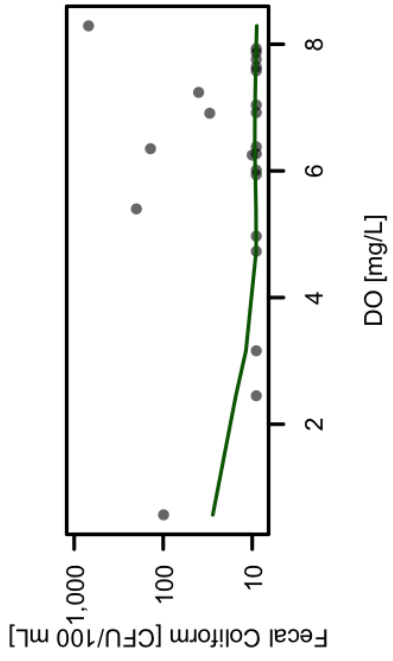


Figure E.3. Scatterplots of Correlations between Physical Wastewater Quality Parameters and log-Transformed Fecal Coliform Concentrations





Descriptive Statistics of Fecal Coliform Concentrations from Retrospective Quarterly Compliance Sampling Dataset

Table E.1. Descriptive Statistics of Fecal Coliform Concentrations Stratified by UV Bulb Deficiency

	N	Mean	SD	GM	GSD	Min	25%	Mdn	75%	Max
UV Bulb Not Deficient	2,382	395	2,596	26.3	7.3	<1	<10	<10	99	80,000
UV Bulb Deficient ^a	65	3,224	9,341	297.3	10.6	<1	150	201	1,510	58,800
NA ^b	269	1,257	9,240	38.5		<1	<10	11	201	120,000
All	2,711	548	4,081	29.0	7.9	<1	<10	<10	130	120,000

^aUV bulb off or OSS flow bypassing the UVD unit.

^bUV bulb status could not be determined from inspection reports.

Descriptive Statistics Used to Determine Appropriate Model for Analysis of Regulatory Post-UV Fecal Coliform Sampling Dataset

Other OSS Deficiencies

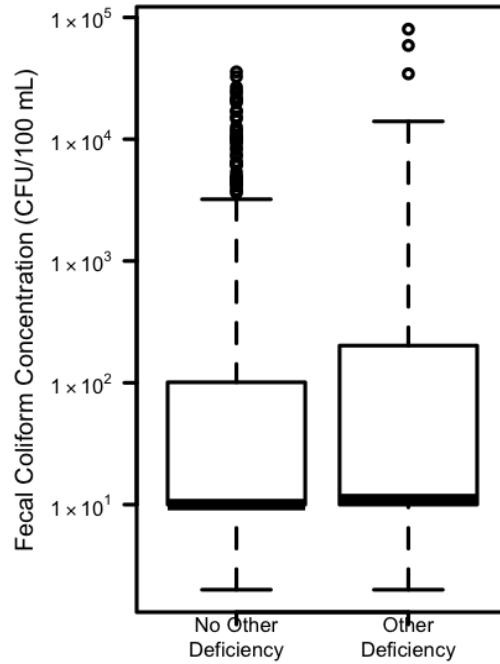


Figure E.4. Boxplot of log-Transformed Fecal Coliform Concentrations Stratified by Presence of Deficiency in OSS Component Other than the UVD Unit

Table E.2 Descriptive Statistics of Fecal Coliform Concentrations Stratified by Presence of Other OSS Deficiency

	N	NA	Mean	SD	GM	Min	25%	Mdn	75%	Max
No Other Deficiency	2025	2	402	2,097	27.2	<1	<10	<10	100	35,701
Other Deficiency ^a	265	2	1,018	6,536	34.9	<1	<10	10	201	80,000
NA ^b	426	1	952	7,660	34.9	<1	<10	10	201	120,000
ALL	2716	5	548	4,081	29.0	<1	<10	<10	130	120,000

^aDeficiency in OSS component other than UVD unit. Includes aerator malfunction, overdue pumping, and lack of electrical power to the OSS.

^bOSS status could not be determined from inspection reports.

Table E.3 Prevalence of Other Deficiencies in OSSs with and without UV Bulb Deficiencies

	No Deficiency	Other Deficiency	Prop. With Other Deficiency
UV Bulb On	1,967	231	11%
UV Bulb Deficient	39	24	38%

Other OSS deficiencies seem to be associated with UV bulb deficiency in the sample, and although the descriptive statistics do not indicate that other OSS deficiencies are associated with fecal coliform concentrations, it is theoretically probable that they would be associated. Therefore, the Tobit regression model of the association between UV bulb deficiency and fecal coliform concentrations adjusted for other OSS deficiencies as a possible confounder.

Age of UV Bulb

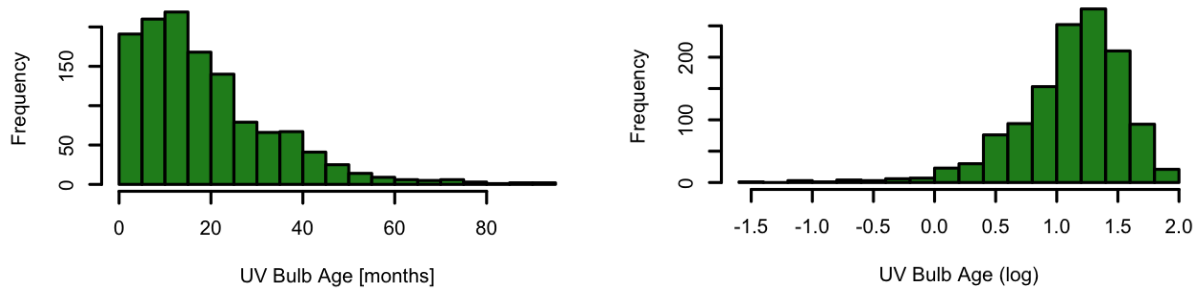


Figure E.5. Distributions of Non-transformed and log₁₀-Transformed Age of UV Bulbs at Time of Quarterly Compliance Sampling

The bulb age variable was transformed with a log-base 10 because it fits a log-Normal distribution better than a Normal distribution.

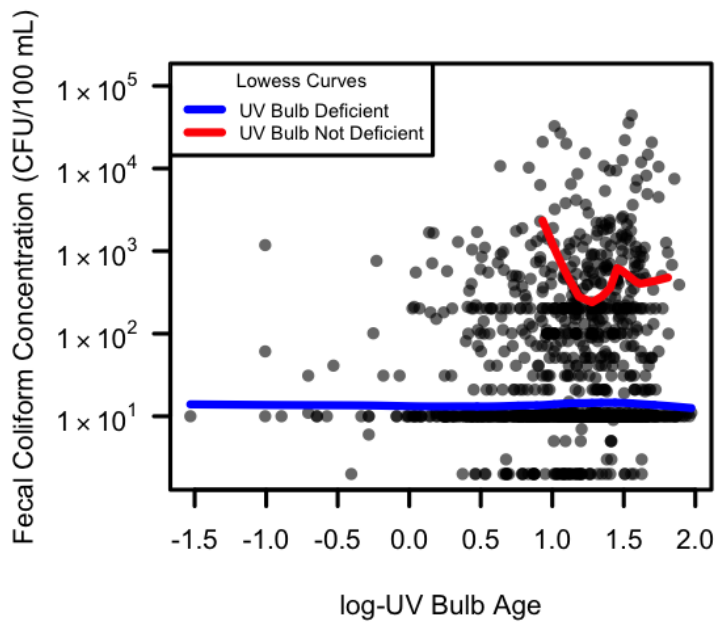


Figure E.6. Associations Between Fecal Coliform Concentration and UV Bulb Age, with Lowess Lines Indicating Difference in Association Depending on UV Bulb Deficiency

Table E.4. Descriptive Statistics of Fecal Coliform Concentrations, Stratified by Age of UV Bulb

	N	NA^a	Mean	SD	GM	Min	25%	Mdn	75%	Max
<1 year	481	0	349	2,272	23.1	<1	<10	<10	99	32,550
1-2 years	433	0	311	1,485	26.9	<1	<10	<10	100	19,999
2-3 years	177	1	1,026	4,736	49.7	<1	<10	10	205	44,101
3-4 years	108	0	649	2,189	37.4	<1	<10	<10	201	14,701
> 4 years	55	0	885	3,265	35.1	<10	<10	<10	114.5	20,701
NA	1462	4	607	5,012	29.1	<1	<10	10	150	120,000
All	2716	5	548	4,081	29.0	<1	<10	<10	130	120,000

^aNA indicates missing data.

Table E.5. Descriptive Statistics of Age of Bulb in Months, Stratified by UV Bulb Deficiency

	N	NA	Mean	SD	GM	Min	25%	Mdn	75%	Max
No UV Deficiency	2,382	1,244	18.3	14.8	12.5	0.0	7.5	14.7	24.2	93.8
UV Deficiency ^a	65	43	29.0	15.0	25.1	8.6	16.2	28.4	40.4	64.3
NA ^b	269	175	23.2	14.5	17.1	1.0	13.9	21.4	34.1	62.5
All	2,716	1,462	18.9	14.9	12.9	0.0	7.8	15.1	25.4	93.8

^aUV bulb off or OSS flow bypassing the UVD unit.

^bUV bulb status could not be determined from inspection reports.

Based on the scatter plot above and theoretical knowledge, the age of the UV bulb could be associated with effluent fecal coliform concentrations when the UV bulb is on, but it is unlikely that it would be associated with fecal coliform concentrations when the UV bulb is off. Therefore, the Tobit regression model for the association between UV bulb deficiency and fecal coliform concentrations did not adjust for age of UV bulb as a confounder, but a subgroup sensitivity analysis was performed to examine the effect of UV bulb age on fecal coliform concentrations when the UV bulb was on.

Subgroup Sensitivity Analyses for Tobit Regression Model of Fecal Coliform Results from Regulatory Sampling

Table E.6. Tobit Regression Model Estimates for the Association Between Geometric Mean Fecal Coliform Concentrations and UV Bulb Age

	Raw Model			Exponentiated Model		p-value
	Estimate	SE	95% CI ^a	Estimate	95% CI ^a	
Intercept	0.489	0.078	0.34–0.64	3.08	2.19–4.34	<0.001
UV Bulb Age (log ₁₀)	0.021	0.046	-0.07–0.11	1.05	0.85–1.29	0.658
Other Deficiency ^b	-0.068	0.080	-0.23–0.09	0.85	0.59–1.23	0.397

^a95% confidence interval
^bDeficiency in OSS component other than UVD unit. Includes aerator malfunction, overdue pumping, and lack of electrical power to the OSS.

On average, the GM fecal coliform will be 4.8% higher for each 10% increase in age of the UV bulb. Based on the 95% confidence interval, we could reasonably expect the GM fecal coliform to be between 15% lower and 29% higher per 10% increase in age. A p-value of 0.658 indicates that we cannot reject the null hypothesis of no association between UV bulb age and fecal coliform concentrations.

Table E.7. Multivariate Tobit Regression Model Estimates for Geometric Mean Fecal Coliform Concentrations with Sample Location Included

	Unadjusted Model				Adjusted Model			
	Estimate	SE	95% CI ^a	p-value	Estimate	SE	95% CI ^a	p-value
Intercept	5.44	0.21	2.2-13.7	<0.001	3.42	0.19	1.5-8.0	0.004
UV deficiency ^b	84.3	0.55	7.0-1,020	<0.001	90.4	0.53	8.1-1007	< 0.001
Other deficiency ^c	0.55	0.29	0.1-2.1	0.38	0.61	0.31	0.1-2.5	0.490
Sample Location ^d					0.82	0.34	0.8-16.9	0.087

^a95% confidence interval
^bUV bulb off or OSS flow bypassing the UVD unit
^cDeficiency in OSS component other than UVD unit. Includes aerator malfunction, overdue pumping, and lack of electrical power to the OSS.
^dIndicator variable for sample collection from pump chamber.

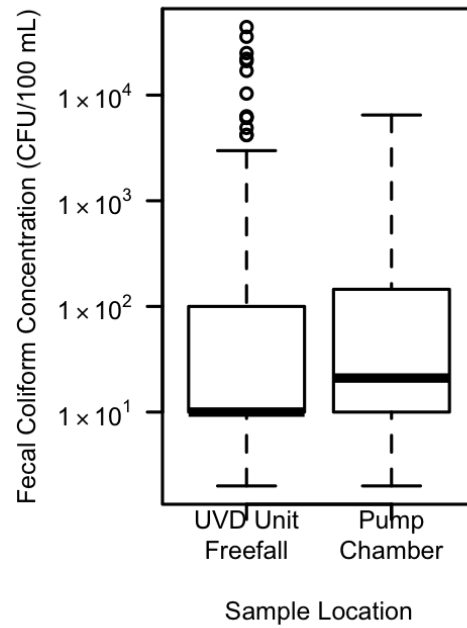


Figure E.7. Fecal Coliform Concentrations in Retrospective Compliance Samples with Known Sampling Location, Stratified by Sampling Location (UVD Unit Freefall and Pump Chamber)

After adjusting for sample location, the exponentiated estimates and standard errors of the multivariate Tobit regression model do not change significantly. Based on this analysis, we can conclude that the sampling location is not confounding the results of the Tobit regression model for the association between UV bulb deficiency and fecal coliform concentrations.

Comparison of Pump Chamber Fecal Coliform Concentration Distributions Stratified by UV Bulb Status

To compare the distributions of pump chamber fecal coliform concentrations stratified by UV bulb status, a synthetic distribution of the fecal coliform concentrations from OSSs with functioning UV bulbs was generated using Crystal Ball. First, a binomial distribution was fit of the probability of detecting fecal coliforms (above the lower limit of detection) in an OSS with a functioning UVD unit. This distribution had a 65.7% probability of detection. A custom distribution was then generated using the detected positive values in OSSs with a functioning UVD unit. A multiplicative combination of the two distributions created a new synthetic distribution to describe which values would likely be observed in a larger sample from OSS with functioning UVD units.

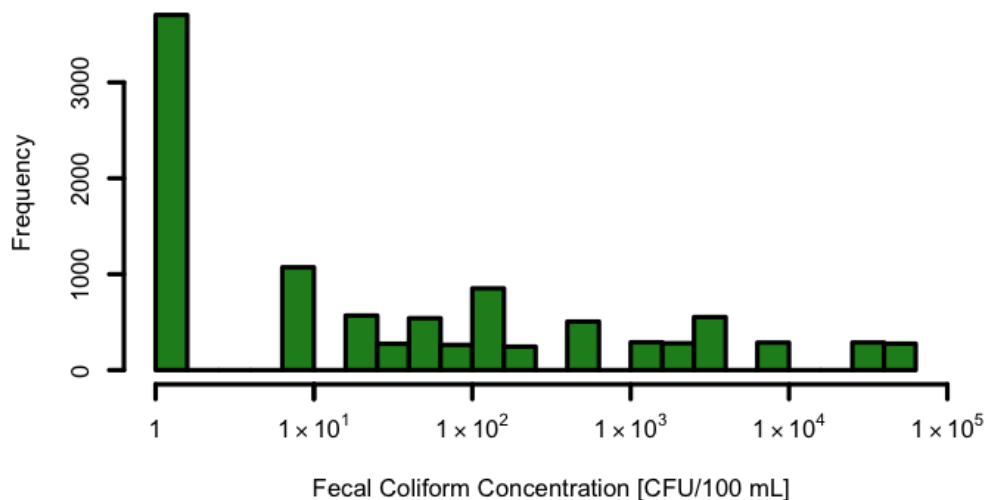


Figure E.8. Synthetic Beta-Poisson Distribution Generated from the Detected Fecal Coliform Concentrations in Pump Chambers of OSSs with Functioning UVD Units

Based on the synthetic distribution that was generated, the values above the lower limit of detection for non-working systems were above the 80th percentile, with the maximum exceeding

the 100th percentile for the working systems. Therefore, it is likely that the fecal coliform concentrations in pump chambers following UVD units that are not functioning are different than those from pump chambers following UVD units that are functioning. However, because of the small sample size, it is not possible to determine whether UVD unit status influences pump chamber fecal coliform concentrations.

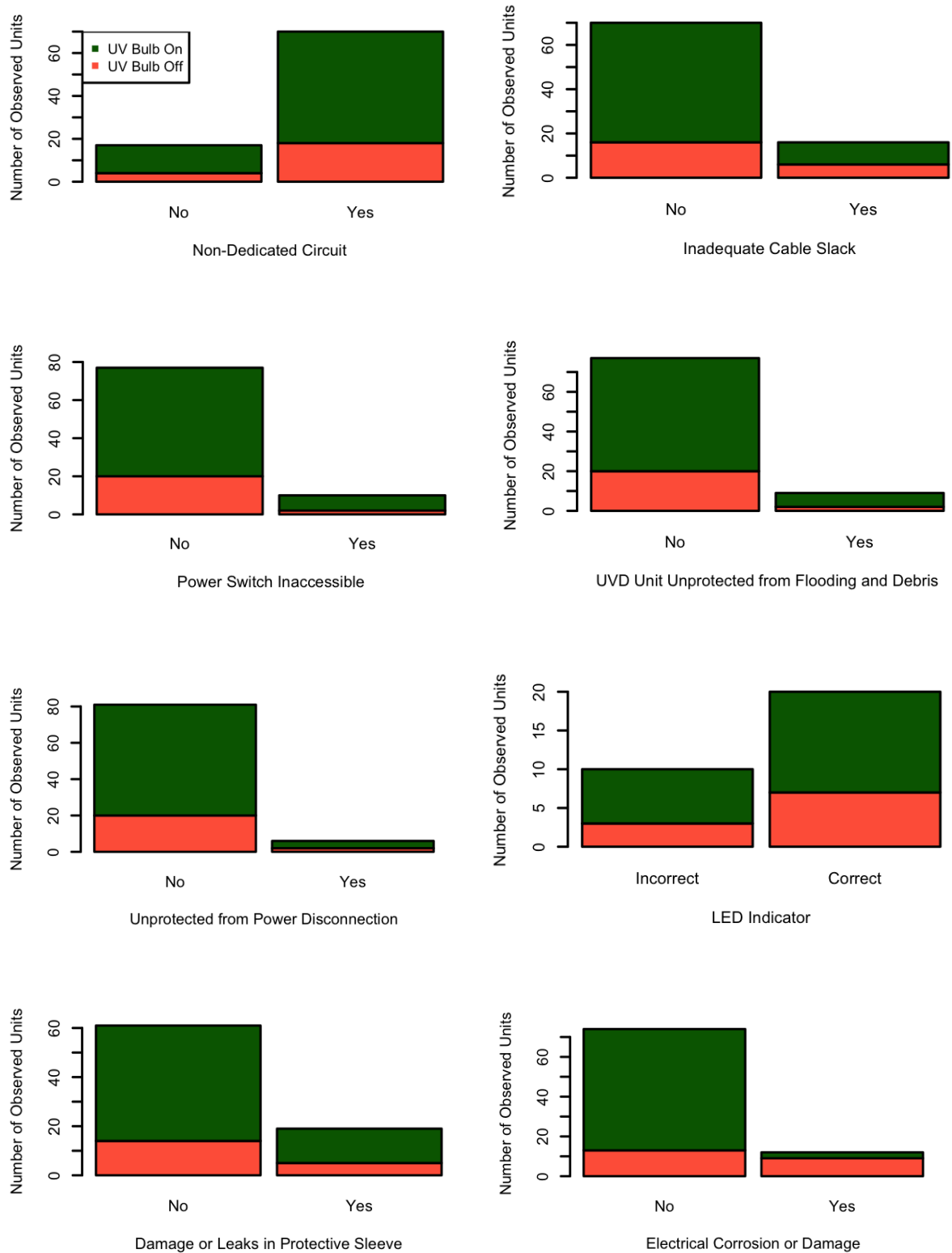
Descriptive Statistics for Pump Chamber Physical Wastewater Quality Parameters

Although fecal coliform concentrations in the pump chamber samples were on average higher than the UVD unit effluent samples (higher GM and maximum concentration), physical wastewater quality indicators are more similar between the two sampling locations. As indicated in Table E.8, the mean and range for temperature, pH, conductivity, turbidity, and UVT are similar in UVD unit effluent and pump chamber samples. Dissolved oxygen levels are lower in the pump chamber, which can be explained by the UVD unit's proximity to the ATU, where oxygen is added to the wastewater to maintain aerobic conditions. Due to the high correlations of temperature, conductivity, and UV transmittance (Spearman's rho >0.90), and pH and turbidity (Spearman's rho >0.80), pump chamber measurements of these parameters are representative estimates of UVD unit effluent quality.

Table E.8. Wastewater Quality of UVD Unit Effluent Compared to Pump Chamber

	UVD Unit Effluent Mean ± SD (min-max) n=22	Pump Chamber Mean ± SD (min-max) n=45	Spearman's rho Correlation Coefficient^a
Fecal Coliform (CFU/100 mL)^b	18.1 ± 3.6 (<10-690)	89 ± 17 (5-150,000)	0.55 (p=0.002)
Temperature [°C]	21.1 ± 2.5 (16.7-25.6)	21.2 ± 2.6 (16.8-27.2)	0.95 (p<0.001)
pH	6.7 ± 0.8 (4.8-8.3)	6.8 ± 0.6 (4.5-8.1)	0.89 (p<0.001)
Dissolved Oxygen [mg/L]	6.8 ± 2.0 (5.4-8.3)	3.6 ± 1.9 (0.3-8.6)	0.38 (p=0.084)
Conductivity [µS/cm²]	612 ± 302 (227-1,308)	605 ± 235 (246-1,149)	0.94 (p<0.001)
Turbidity [NTU]	20.4 ± 19.6 (0-60.6)	17.7 ± 22.3 (0-77.5)	0.85 (p<0.001)
UVT [%]	44.5 ± 17.7 (13.3-74.0)	47.5 ± 17.2 (7.1-81.9)	0.92 (p<0.001)
^a Correlation coefficient of the measurements of the given parameter in UVD unit effluent and in pump chamber wastewater.			
^b Descriptive statistics are GM ± GSD (min-max) and correlation coefficient Kendall's tau-B.			

Figure E.9. Proportion of UVD Units with UV Bulb Off Stratified by Indicators of Suboptimal Installation, UVD Unit Characteristics, and UVD Unit Performance as Predictors



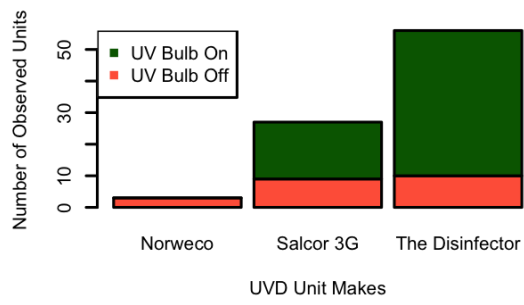
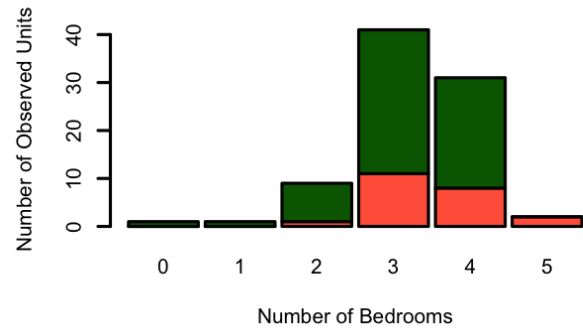
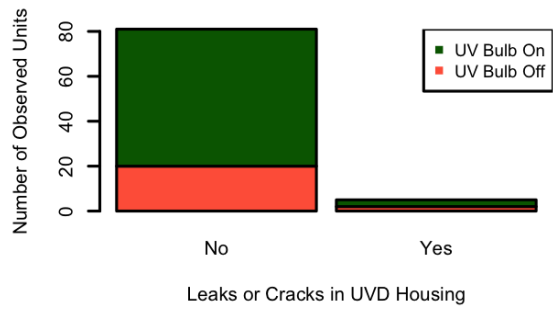
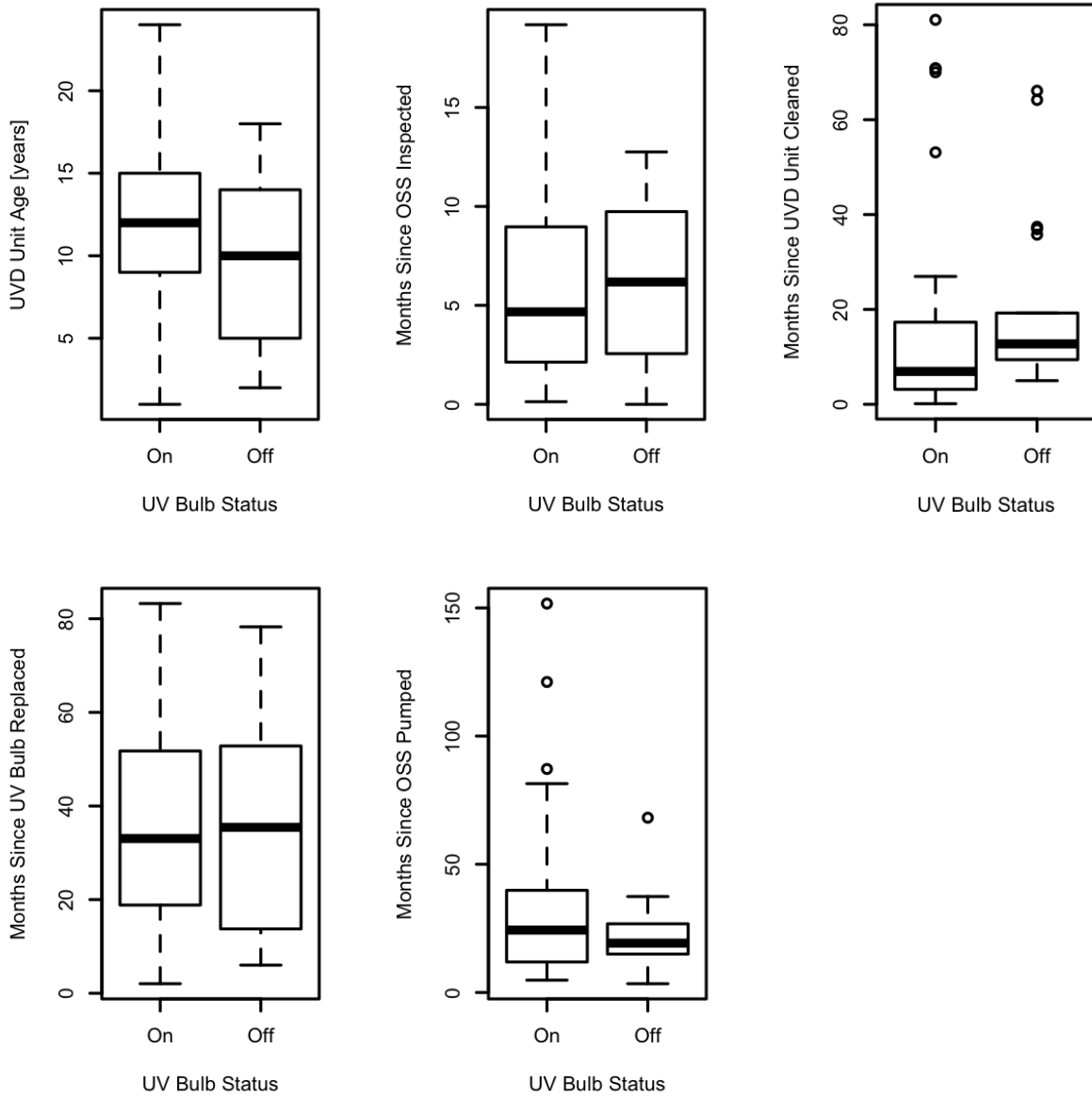


Figure E.10. Differences in UVD Unit Installation and Maintenance Characteristics Stratified by UV Bulb Status



Odds Ratios for UV Bulb Malfunction with Indicators of Suboptimal Installation, Maintenance, and Performance as Predictors

Table E.9. Odds Ratios for UV Bulb Malfunction for Binary Variables, Calculated with Fisher’s Exact Test

	OR (95% CI)	p-value
Electrical corrosion or damage	13.5 (2.87-88.0)	<0.001
UV bulb with protective sleeve inaccessible	3.05 (0.209-44.6)	0.269
Inadequate cable slack	2.01 (0.516-7.29)	0.34
Leaks/cracks in UVD housing unit	2.01 (0.158-18.9)	0.599
UVD unit not protected from power disconnection	1.52 (0.128-11.5)	0.64
Damage or leakage in protective sleeve	1.2 (0.286-4.37)	0.764
UVD unit on non-dedicated circuit	1.12 (0.294-5.34)	1
UV location	0.95 (0.270-3.89)	1
UVD housing unit unprotected from weather or debris	0.816 (0.077-4.79)	1
LED indicator incorrect	0.802 (0.101-5.12)	1
Power switch inaccessible	0.715 (0.068-4.02)	1

Table E.10. Odds Ratios for UV Bulb Malfunction for Non-Binary Variables, Calculated with Logistic Regression

	Standardized OR (95% CI)^a	Unstandardized OR (95% CI)	p-value
Biofilm Deposit rank	8.39 (2.63-26.8)	2.98 (1.64-5.42)	<0.001
# of bedrooms	2.62 (0.904-7.61)	1.82 (0.940-3.51)	0.0753
Months since UV unit last cleaned	1.68 (0.717-3.93)	1.02 (0.991-1.04)	0.229
Months since last inspection	1.34 (0.482-3.72)	1.04 (0.918-1.17)	0.571
Months since UV bulb last replaced	0.854 (0.230-3.18)	1.00 (0.966-1.03)	0.811
Age	0.420 (0.154-1.14)	0.916 (0.827-1.01)	0.0889
Months since last pumping	0.365 (0.101-1.32)	0.981 (0.957-1.01)	0.122

^a*Categorical and continuous variables were divided by 2 standard deviations to compare the OR magnitude to those of binary variables.*

Male-specific (F+) Coliphage Concentrations in Samples from OSSs with UVD Units

Table E.11. Male-specific (F+) Coliphage Concentrations in OSSs with UVD Units

Sampling Location	Number of Samples	Samples Positive for F+ Coliphage
Septic Tank Influent	6	0
UVD Unit Effluent (Unit Turned Off) ^a	2	0
UVD Unit Effluent (As Found) ^a	3	0
Pump Chamber	23	5 (21.7%) ^b

^a*Holding times exceeded 48 hours (up to 96 hours).*
^b*MPN values of positive samples were: 3, 11, >2500, >2500, and >2500 MPN/100 mL.*

APPENDIX F. RESEARCH TRANSLATION MATERIALS

PRESENTATION AT WASHINGTON STATE ENVIRONMENTAL HEALTH ASSOCIATION 2018 ANNUAL EDUCATION CONFERENCE, MAY 8, 2018

Field Effectiveness of Ultraviolet Disinfection Units in On-site Wastewater Treatment



Meagan Jackson, University of Washington
Washington State Environmental Health Association, 66th Annual Education Conference
May 8, 2018 - Olympia, WA

DEPARTMENT OF ENVIRONMENTAL & OCCUPATIONAL HEALTH SCIENCES
UNIVERSITY OF WASHINGTON SCHOOL OF PUBLIC HEALTH

Project Team

- Washington State Department of Health
 - Randal Freeby, John Eliasson, Leslie Turner, Jeremy Simmons
- University of Washington
 - Tania Busch Isaksen, Scott Meschke
- Tacoma-Pierce Public Health Department
 - Gary Porter
- Thurston County Public Health and Social Services
 - Steve Petersen, Erik Iverson

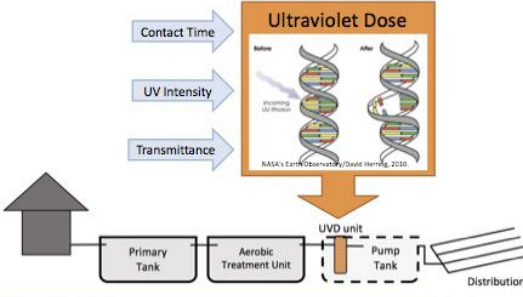
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Outline

- Ultraviolet Disinfection (UVD) Units
- Study Description
- Effluent Quality Findings
- Insights into UVD Performance and Reliability
- Conclusions

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Onsite Ultraviolet Disinfection Units



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Do UVD Units Function in the Field?

In Washington:

- UVD units tested according to bacteriological reduction protocol with NSF/ANSI-Standard 40
 - Treatment Level A: 30-day GM fecal coliform <200 CFU/100 mL
 - Treatment Level B: <1,000 CFU/100 mL
- Maintenance plan is required
 - Thurston: semiannual inspections, quarterly sampling
 - Pierce: annual inspections
- Reports of bulb, electrical failures



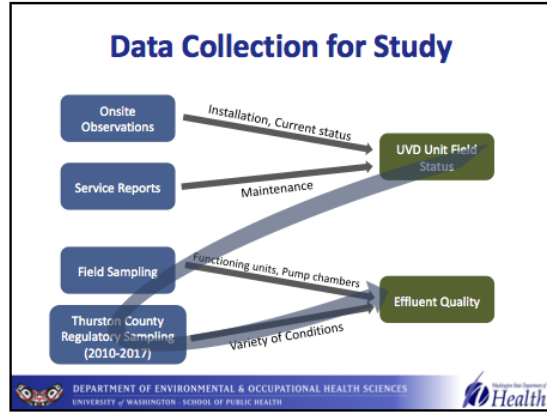
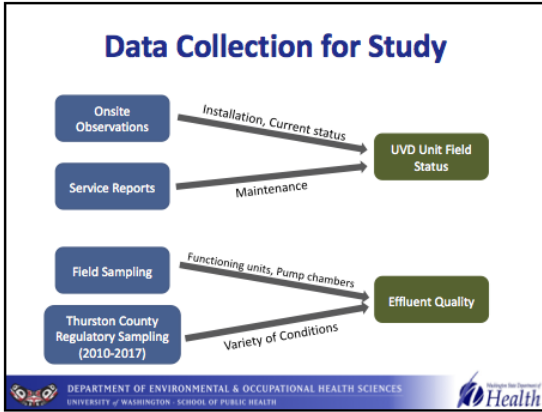
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Study Design

- Invited all owners of UVD units in Pierce and Thurston Counties to participate.
- UVD unit Makes: Salcor 3G (32%), The Disinfecter (64%), Norweco (4%)

	Pierce County	Thurston County
All OSSs with UVD Units	2,034	142
OSSs Evaluated	65	32
Post-UVD Unit Samples	0	22
Pump Chamber Samples	25	28

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Effluent Microbial Quality

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Effluent FC Quality – Field Samples

- UVD units in Thurston Co. have effluent with low fecal coliform concentrations.
- UVD units achieved mean 2.1-log fecal coliform reduction (SD=1).

Thurston County has set Action Levels for each Treatment Standard: two or more of the past four sample results > 2x treatment standard

Descriptive Statistics for FC Measurements in 22 UVD Units in Thurston County	
GM ± GSD	18.1 ± 3.6 CFU/ 100 mL
Mean ± SD	61.1 ± 149.1 CFU/ 100 mL
Minimum	< 10 CFU/ 100 mL
Median	< 10 CFU/ 100 mL
Maximum	690 CFU/ 100 mL
Below detection limit	16 (73%)
Below Action Level A (400 CFU/ 100 mL)	21 (96%)
Below Action Level 2 (1,600 CFU/ 100 mL)	22 (100%)

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Wastewater Quality in Pump Chambers After UVD Units

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Pump Chamber Fecal Coliform Results

	N	Mean ± SD	GM ± GSD	Mdn	75 th %	Max
UVD Working	37	2,875 ± 10,322	68 ± 13	<10	225	56,000
UVD Not Working ^a	10	15,878 ± 47,177	75 ± 40	<10	1,295	150,000
Unknown ^b	6	36,106 ± 80,504	1,073 ± 13	745	11,532	>200,000

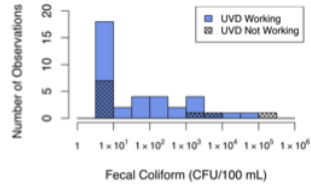
^aUV bulbs classified as not working if UV bulb was off or had high biofilm deposit.
^bUV bulb status could not be determined.

- Pump chambers had higher FC levels (likely due to bacterial regrowth).
- Mean FC higher with malfunctions, but also very large standard deviations.

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Pump Chamber Wastewater Quality

- Do not have enough power to detect a difference if there is one.
- Importance of other factors that influence wastewater quality:
 - Wastewater generation
 - Pump chamber dosing, pumping



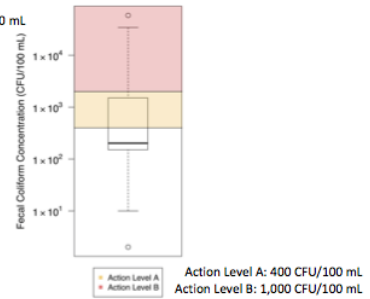
Pump Chamber Samples: Other Issues

Pump Chamber FC (CFU/100 mL)	Post-UV FC (CFU/100 mL)	No UV FC (CFU/100 mL)	UV Bulb Status	Biofilm Level	PC Turbidity (mg/L)	Other Observations
> 200,000			On		63.3	Cracks in housing unit, unit flooded with water
150,000			On	High	76.4	Commercial site not functioning well
56000	99	120000	On	Med	16.0	ATU off before arrival
30000	139	6937	On	Low	12.4	Unknown bulb age
15000					38.4	No electricity to bulb
9000	200	6667	On	None	69.5	
7000			Off	High	64.9	
3000			On	Low	77.5	
3000	10	7297	On	Low	36.1	Large grains in sample
2000			On	Low	76.9	
1723			Off	Med	2.1	

Retrospective Quarterly Compliance Sampling

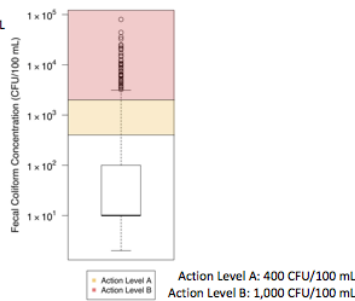
Effluent Quality with Deficient UVD Unit

GM = 297.3 ± 10.6 CFU/100 mL
Min <1
Max = 5.9×10⁴



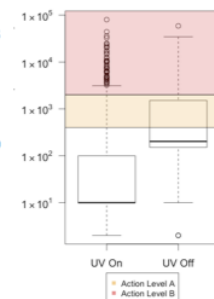
Effluent Quality with Working UVD Unit

GM = 26.3 ± 7.3 CFU/100 mL
Min <1
Max = 8.0×10⁴



Effluent Quality and UVD Unit Status

- GM FC concentration: **122 times higher** when UV bulb deficient
 - 95% CI=36-428, p-value <0.001
 - Adjusted for other OSS deficiencies
- Odds of exceeding Action Level **7.48 times higher** when UV bulb deficient
 - 95% CI: 4.03-13.9, p-value<0.001
 - Adjusted for other OSS deficiencies



Action Level Exceedance

- Field samples:
 - 4% UVD unit effluent samples >400 CFU/100 mL (95% confidence interval: 0-14%)
- Retrospective compliance samples:

Proportion of OSSs Exceeding Action Level (in %)			
Treatment Level	UV Bulb On	UV Bulb Deficient	All
A/1	9.2	45.5	10.4
2	4.6	27.6	5.3
B	5.6	42.9	6.6
All	6.8	36.2	7.4

Possible Explanations for High Microbial Loads after UVD Units in the Field

Malfunctioning UVD Units



25% of UV bulbs were not burning.

- 40% of UVD units in Pierce had a bulb that wasn't burning.
- All bulbs were burning in Thurston.

Risk Factors for Bulb Malfunction



Biofilm Buildup: 10%



Electrical Damage: 15%



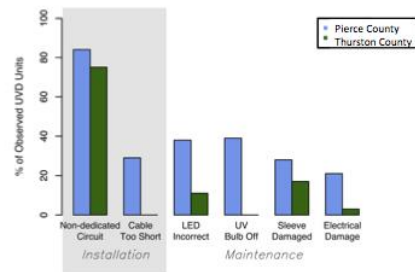
Lack of access: 15%
Limited cable slack: 18%

Pretreatment Performance

- Pretreatment and ATU performance can impact effluent fecal coliform concentrations.
 - Correlation between conductivity and FC: 0.51
 - Correlation between turbidity and FC: 0.37

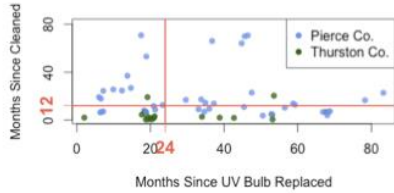


County-Level Differences in UVD Units



Maintenance Differences

- Different management plans had different maintenance frequency and malfunction prevalence.



Other Insights



- Differences in homeowner engagement
- Field sample a strong tool for service providers

Conclusions

- When ATU and UVD unit are properly functioning, post-UVD unit effluent fecal coliform is low and reduces likelihood of exceeding treatment standards.
- Other aspects of OSS are important:
 - ATU and pump chamber
 - O&M management plan
 - Operation and maintenance



Recommendations



Thank you!

For further questions, contact:

Meagan Jackson
meaganja@uw.edu

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REPORT TO STUDY PARTICIPANTS



DEPARTMENT OF ENVIRONMENTAL & OCCUPATIONAL HEALTH SCIENCES
UNIVERSITY of WASHINGTON · SCHOOL OF PUBLIC HEALTH



Date

Dear Study Participant,

We are sending you a report of **the ultraviolet disinfection study** that you participated in last summer. We apologize for the delay in sending it to you. Thank you for volunteering for the study and welcoming the researchers to look at your septic system! We could not have finished the study without your valuable contribution.

Our study's goal was to learn more about how ultraviolet disinfection (UVD) units are working in Pierce and Thurston Counties. The study results show that UVD units reduce bacteria to very low levels when they are properly maintained and functioning. However, 25% of the observed units were not working because the UV bulb was not glowing.

More information about the study findings and the individual results for your UVD unit are included in this letter. Washington State Department of Health (WADOH) will use the study's combined results to evaluate necessary changes to UVD unit maintenance and operation.

Please contact us if you have any questions about the study or your individual results. We would be happy to talk with you!

Sincerely,

Meagan Jackson

University of Washington,
Graduate Research Assistant
meaganja@uw.edu

STUDY ABOUT ULTRAVIOLET DISINFECTION (UVD) UNITS

University of Washington and WADOH researchers evaluated 97 UVD units during June-August, 2017. We visited 32 properties in Thurston County and 65 in Pierce County. We evaluated your UVD unit on XXXX.

The UVD unit is an important part of your on-site sewage system. It removes additional microorganisms (bacteria, viruses, and others) from your wastewater because the soil on your property cannot remove enough microorganisms to protect nearby surface water or shallow groundwater.

UVD UNIT STATUS



YOUR UV BULB WAS ON.

If the bulb is off, the UVD unit does not disinfect wastewater. The bulb should be on at all times.



YOUR ELECTRICAL COMPONENTS WERE NOT DAMAGED.

If the electrical wiring or connections are damaged, the UV bulb may not be able to function properly and glow constantly.



YOUR UV BULB HAD LOW BIOFILM DEPOSIT.

Biofilms are a collection of organic material and microorganisms. Thick biofilms prevent the UV light from reaching the wastewater and killing microorganisms.



YOUR UV BULB PROTECTION WAS DAMAGED.

If the quartz (and sometimes Teflon) that surrounds the bulb is damaged, it can limit disinfection or the bulb can break during maintenance.

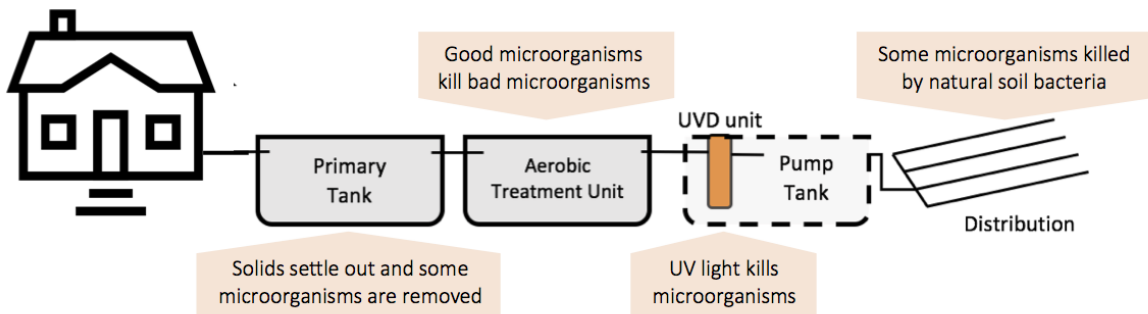
We also saw that your LED indicator light was not burning, even though the UV bulb was on. You should follow up with your certified maintenance provider to correct these problems.

Among the UVD units we observed:

- 25% did not have glowing UV bulbs.
- 8% had a high biofilm deposit.
- 14% had damaged electrical components.
- 24% had a damaged protective sleeve.

A higher percentage of the UVD units with these problems were in Pierce County. Pierce County's maintenance requirements for UVD units are less rigorous than Thurston County's.

YOUR UVD UNIT IS AN IMPORTANT PART OF YOUR SEPTIC SYSTEM.



WASTEWATER QUALITY

If the water leaving the UVD unit has too many microorganisms, it can pollute the groundwater that we drink or the lakes, rivers, and beaches that we play in. If people contact the microorganisms, they may get sick.

We collected wastewater from 22 UVD units in Thurston County and 45 pump chambers in both Pierce and Thurston counties. We also collected wastewater that had not been treated by the UVD unit in 17 septic systems. The results show that the UVD units killed more than 99% of the fecal coliform bacteria in the wastewater.

In Thurston County, all of the observed UV bulbs were on and the UVD units were functioning well. The wastewater in all of these units met the site's treatment requirement for fecal coliforms. Only one wastewater sample exceeded the strictest treatment requirement of 200 CFU/100 mL (for Treatment Level A). Samples collected in Thurston County between 2010 and 2017 show that the average fecal coliform level is at least 18 times higher in UVD units when the UV bulb is off (and it can be up to 1,500 times higher). This means that UV disinfection units are important to kill microorganisms.

The study results show that when the UV bulb is on, the wastewater in pump chambers is probably better quality than when the UV bulb is off, but we need more results to know for sure.

	YOUR UVD UNIT	Average	Recommended Range
Fecal coliform (CFU/ 100 mL)	18	18	200 or less ¹
Turbidity (NTU)	20	20	Lower is better
Conductivity (µS/cm)	612	612	Lower is better
pH	6.7	6.7	6-9 ²
Dissolved Oxygen (mg/L)	6.1	6.1	2.0 or more
UV Transmittance (%)	45	45	60 or more ³

The wastewater after your UVD unit had poorer quality than most in the study. It is possible that your aerobic treatment unit was not functioning properly when we evaluated your UVD unit. However, the fecal coliform results met the treatment requirement for your septic system.

You can follow up with your certified maintenance provider to decide whether you need to fix your system.

Wastewater Quality Measurements

To determine the quality of wastewater in UVD units, we measured:



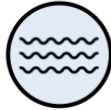
Fecal Coliform. This group of bacteria does not cause disease, but it shows how well the wastewater has been cleaned. If we measure a lot of fecal coliforms, microorganisms that can cause disease may be present in the wastewater.



Turbidity and Conductivity. These are measures of how many solids are in wastewater. Solids can interfere with UV disinfection, so turbidity and conductivity should be low for UVD units to work well. If ATUs are not working correctly, turbidity and conductivity can be high.



pH and Dissolved Oxygen. These are measures of how well the ATU is working. If pH is too low or too high, or if dissolved oxygen is too high, the ATU will not remove as many microorganisms.



Ultraviolet Transmittance. This is a measure of how UV light travels through water. If transmittance is low, the UV light cannot reach or kill all the microorganisms in the wastewater.

