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Field evaluation of a novel UV water disinfection system for use in underserved rural communities

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Abstract

Reliable, robust, and inexpensive disinfection systems are needed to expand water security in remote and underserviced areas. This paper reports on the deployment and evaluation of a novel UV water disinfection system in a remote rural community. Prior laboratory tests indicated a 7.12 log10 reduction of the bacteriophage MS-2 at a flow rate of 9.46 L/min, which corresponds to a supplied UV dose 215 mJ/cm^2. Further tests in water containing turbidity levels up to 18 NTU showed *E. coli* removal remaining above the 5 log10 level. Field testing was performed at a Native American reservation in Northern California where the system was used to treat groundwater obtained from a well with a known fecal contamination. The system was powered by solar panel and was operated on-demand for extended periods. Tests on the treated water showed that the system exceeded the standard of disinfection required for drinking water. © 2018 Water Environment Federation

Practitioner points

- A novel system for water disinfection with UV light is described.
- Laboratory and field tests showed high levels of disinfection achieved even at low UVT and high turbidity.
- System is robust, reliable and inexpensive to produce thus suitable for use in underserved communities.

Key words

underserved communities; UV disinfection; water safety

Introduction

Centralized services typically found in major cities, such as drinking water and wastewater treatment, are expensive and unattainable for many small cities and remote locations (Cherunya, Janezic, & Leuchner, 2015; Huang et al., 2018). This is true in many places other than in the developing world. For example, as of 2014, over 1 million Californians still did not have safe drinking water either because their publicly supplied water contains constituents over the regulated Maximum Contaminant Level (MCL) or because they rely on insecure private wells that receive no treatment at all (SWRCB, 2016). Similarly, as of 2014, 432 public water systems have been unable to supply safe drinking water to their communities for years and sometimes even decades in California's San Joaquin Valley (SWRCB, 2016). Therefore, these communities must rely on either purchasing bottled water or treating their own water onsite.

An essential part of the onsite, point-of-use disinfection of the drinking water is to prevent the consumption of fecally contaminated water thus reduce the risk of transmission of enteric viral and bacterial diseases (Firth et al., 2010; Sobsey, Stauber, Casanova, Brown, & Elliott, 2008). Personal and household water treatment devices and chemical treatment devices have been developed to meet this need (Clasen, 2015; Sobsey, 2004). For example, chemicals, such as chlorine and iodine, have a long history of use to treat water, but these treatment methods can negatively alter the taste of the water and can also create harmful disinfection by-products. Filtration systems are also available; however, many fail to remove viruses, dramatically reduce the flow rate, and require the water to be treated in batches. Treatment with UV light is an attractive alternative treatment option because it is effective at treating waterborne pathogens, provides rapid and continuous treatment, and does not create any disinfection by-products (Metcalf & Eddy, Inc. et al., 2013). However, existing commercial UV systems are expensive to purchase and operate and, moreover, require a degree of technical ability that is not available in many underserved communities. Many of these drawbacks to the commercial systems arise from their basic design. This consists of one or more UV lamps that are inserted inside quartz tubes and placed within the body of water being treated. As a result, the problem of "fouling" occurs wherein the quartz tubes become covered by organic and inorganic residues that significantly reduce the intensity of UV radiation and eventually lead to failure to achieve adequate inactivation. Anecdotal evidence indicates that many operators of such systems are not aware of the extent of the "fouling" problem, or of the rapidity of its occurrence. Even when the importance of frequent cleaning of the quartz tubes is emphasized, issues of lack of resident technical expertise in underserved communities arise, giving rise to a false sense of security associated with the consumption of water that has flowed through the UV system without receiving adequate UV dose to inactivate target pathogens.

In recent years, a number of studies have been performed to investigate various aspects related to the use of UV disinfection in underserved communities (Anon., 2009; Brownell et al., 2008; Lui et al., 2014; Reygadas, Gruber, Ray, & Nelson, 2015; Sun, Liu, Cui, & Liu, 2013). Vidal et al. (1999) and Vidal and Diaz (2000) examined the potential use of compound parabolic reactors to disinfect water supplies in rural communities and reported successful inactivation of coliforms by UV-A from incident sunlight at competitive costs. In this paper, we introduce a UV system that has been developed to provide a better alternative to the commercially available system, specifically with regard to its suitability for use in underserved communities. Details of this system, and of both the laboratory and field tests conducted for its evaluation, are reported next.

Materials and methods

The UV system

Two features distinguish the new system from those available commercially: The UV lamps do not come in contact with the water, and hence, the problem of "fouling" does not occur, and the water that flows through it does so in the form of a strong swirling motion that ensures exposure of all pathogens present in the untreated water to the appropriate UV dose and, also, ensures that the system is self-cleaning, thereby eliminating the need for frequent maintenance. The way in which these distinguishing features are obtained can be seen from Figure 1, which shows a computer-aided design rendering of the system. The core of this system consists of a quartz tube whose diameter and length are sized according to the expected flow rate of water to be treated. Quartz is one of the few materials suitable for this application since it allows for 96% of the incident UV radiation at the germicidally effective wave length of 254 nm to pass through it. The UV lamps, the number of which again depends on the flow rate and on the pathogenic load in the untreated water, are arranged outside the quartz tube. When operated, the lamps operate without being in contact with the water. Also, with the lamps placed outside the water means that they can be replaced without the entire system being disconnected and drained.

The quartz tube was of length L = 400 mm and inner diameter D = 70 mm giving a total volume of 1.54 L. The residence time was thus approximately 8 s. The tests were predominantly performed with two low-pressure UV lamps rated at 30 W each producing a theoretical lamp intensity of 1.5 W/cm^2. The actual light intensity at the axis of the quartz cylinder, where it is expected to be at its lowest value after being attenuated by the quartz walls and the water, was not measured. However, when dry, this was measured at 2.78 ± 0.127 mW/cm^2. Thus, assuming uniform intensity throughout the quartz tube, the UV dose delivered by each lamp is estimated to be 187 mJ/cm^2.

At inlet to the quartz tube, a diffuser having an included angle of 45° is installed so as to transition of flow from a pipe having the dimensions of a domestic water-supply system, to the larger diameter of the quartz tube to gradually reduce the flow velocity, thereby keeping the hydraulic energy losses associated with the velocity change to a minimum. Within this diffuser, static guide vanes are inserted. Their task is to impart a strong swirling motion to the inlet flow. As previously mentioned, this has the dual benefit of enhanced turbulent mixing, and the provision of a mechanism for self-cleaning due to the high levels of shear stress generated at the inside walls of the quartz tube. At outlet, a nozzle, also having an included angle of 45°, is installed to conveniently connect the large-diameter quartz tube to the domestic water supply system. Within this nozzle, another set of static guide vanes is installed for the purpose of enhancing the swirling motion induced at inlet. Finally, the entire assembly of quartz tube and UV lamps is encased within a PVC cylinder to prevent leakage of UV radiation. The inside of this cylinder is lined with aluminum foil to reflect incident radiation back into the enclosure.

The fabrication of this system was made possible only by the availability of 3D printing technology. This was used to manufacture the key components of this system, specifically the inlet and outlet assemblies, and the guide vanes. Figure 1 gives details of these, and the relevant dimensions. Not only was 3D printing essential for creating the complex shapes involved, but it also allowed for rapid and cost-effective experimentation with alternative configurations to ultimately—an optimal design which maximized the swirling motion while keeping the hydraulic losses at a minimum. With the increasing availability and decreasing cost of 3D printing, it is envisioned that the cost to manufacture the key components of this system will become quite modest.

Laboratory evaluation

The National Sanitation Foundation (NSF) and the US Environmental Protection Agency (USEPA) have recommended performance standards for UV disinfection system to ensure a minimum level of performance for the removal of pathogens. The NSF standard requires the removal of at least 99.99% (4-log10 inactivation) of the bacterial coliphage MS-2 (NSF, 2002). Similarly, the USEPA's Long Term 2 Enhanced Surface Water Treatment Rule and Ground Water Rule require 4-log10 removal of viruses, 3-log10 removal of *Giardia lamblia* cysts, and 2-log10 removal of cryptosporidium (USEPA,

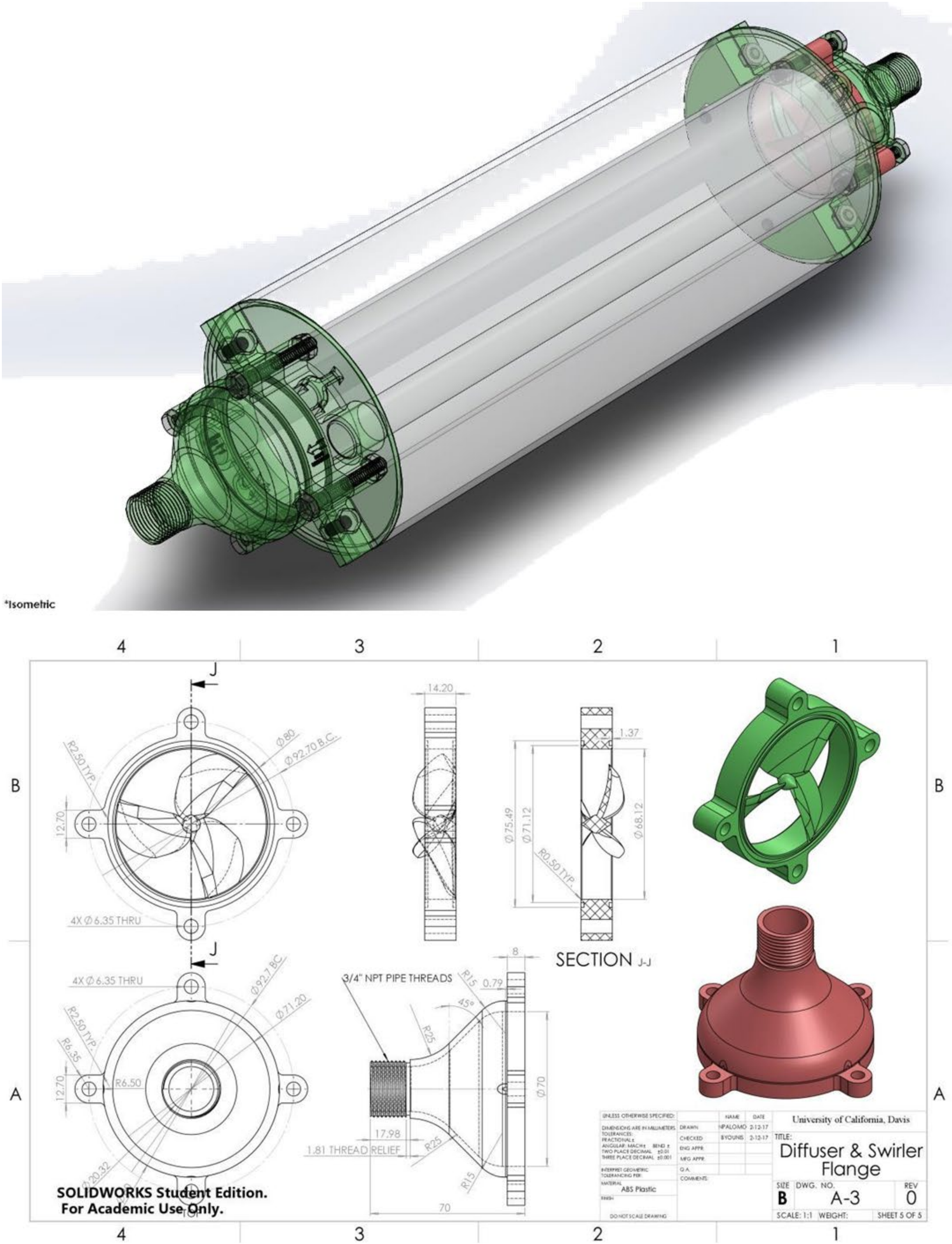

Figure 1. A rendered representation of the UV reactor.

2006a, 2006b). Determination of the UV dose (or fluence) supplied by the system was based on the NWRI recommendations complied in "Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse."

Test water and test conditions

To assess the UV dose applied to the system, the system was spiked with the MS-2 and assessed at two levels of Ultra-Violet Transmissivity (UVT) namely 70% and 90%, and for two flow rates namely 9.46 and 12.9 liters/min. The source water for this testing was unchlorinated City of Davis groundwater at 20 ± 1.2°C and pH 8.3 ± 0.15. The UVTs for this analysis were the original UVT of the City groundwater at 95% and another adjusted to 70% using instant coffee (Pampa) per NWRI's UV guidance manual (NWRI, 2012). The UVT was assessed at wavelength of 254 nm using a Cary Win UV-Vis spectrophotometer (Cary Win 1E, Varian Corp., Houston, TX), and the flow rate was determined using an in-line flow meter (Omega, FL46300 Series). The initial concentration of the MS2 in the source water for the testing was 1.2×10^8 and 3.0×10^8 pfu/ml for a UVTs of 95% and 70%, respectively. For each of the four flow rates and UVTs combinations, three samples were collected before and after the UV for MS-2 testing. Samples were stored at 4°C for <24 hr before being processed at the Biovir Laboratories in Benicia, CA, using the Adam's double agar overlay without RNase method for enumeration (Adams, 1959).

Viral and bacterial analysis

Viral analyses were performed using the MS-2 coliphage (ATCC #15597-B1) to determine the UV dose supplied by the system, and its effectiveness at inactivating viral pathogens (Bolton & Linden, 2003). A solution of the propagated virus and analysis of samples containing the virus were performed by Biovir Laboratories in Benicia, CA. Bacterial analysis were performed using IDEXX Colilert Quanti-Trays to determine total coliform and *E. coli* counts.

The concentrated solutions of *E. coli* used for the turbidity testing and the analysis of the impact of the type of water were prepared in the following manner. The *E. coli* (ATCC #15597) was propagated with Luria Broth (LB; Sigma-Aldrich) and at a 0.4% inoculation. Then, the solution was incubated at 37°C for 12 hr. The cells in the solution were then concentrated by centrifuging the samples for 20 min at 2,500 rpm. The supernatant was decanted, and the pelleted cells were re-suspended in Milli-Q water at room temperature for use during testing so that the color of the LB media did not significantly alter the UVT of the sample water.

Analysis of the impact of water quality

In addition to water from Covelo site, the testing also assessed the performance of the system to disinfect water from a campground in the Mokelumne River Canyon (9/5/2016) and a campground next to Lake Tahoe (9/18/2016). At the Mokelumne River Canyon site, water was collected from the river, the local nonpotable groundwater source, and the potable water line piped in from Pine Grove, CA. The campsite had to move their drinking water from the local groundwater source to the source from Pine Grove, because of iron concentrations exceeding the MCL of 0.3 mg/L. This is important for our testing, since high iron concentrations colors the water and reduces the transmission of the UV light. At the Lake Tahoe campsite, water was collected from the lake at two separate locations adjacent to the campsite. The water was collected by rinsing a sterile bottle three times with the sample water before collecting the sample. For each water type, 38 L of water was collected and then transported to the UCD campus for testing within 12 hr. Once on campus, the samples were stored at 4°C before being processed over the following 7 days.

To determine the impact of the different water qualities, first the water was assessed based on their background characteristics. The oxidation-reduction potential (ORP), conductivity, total dissolved solids (TDS), conductivity, temperature, and pH of the water were measured at the sampling location with a Myron L Company Ultrameter III using the method described in Standard Methods (AWWA) and in conjunction with the instrument manufacturer's instructions. The turbidity and the UVT were assessed on campus using a Hach 2100AN Turbidimeter and a Cary 1E UV visible Spectrophotometer, respectively, in accordance with Standard Methods (AWWA) and manufacturer's instructions.

To assess disinfection performance of the system with each water type, each water type received a dosed of a concentrated solution of *E. coli*. The number of *E. coli* cells that were inactivated in the system before and after passing through it were then assessed using the membrane filtration technique described in Standard Methods (AWWA). Each turbidity level was assessed three times, and three samples were collected before and after the UV for *E. coli* testing from each trial. Samples were stored at 4°C for <24 hr before being processed.

Analysis of susceptibility to turbidity

To assess the impact of turbidity on the system, various concentrations of activated carbon were added to Milli-Q water. To ensure a small particle size, the activated carbon solutions was first crushed, added to the Milli-Q water at a pH of 7 ± 0.16 and a temperature of 20 ± 1.4°C, and then screened with a 20-μm cartridge filter. The activated carbon solution was then added to the system to generate the following levels of turbidity: 0.16 ± 0.05, 3.53 ± 0.85, 6.621.51 ±, 13.3 ± 1.67, and 17.83 ± 2.13 NTU. Each solutions of activated carbon also received a dosed of a concentrated solution of *E. coli*. The number of *E. coli* cells that were inactivated in the system before and after passing through then assessed using membrane filtration technique described in Standard Methods (AWWA). Each turbidity level was assessed three times, and three samples were collected before and after the UV for *E. coli* testing from each trial. Samples were stored at 4°C for <24 hr before being processed.

Field testing location and test conditions

The field tests were carried out at Covelo—CA. This community is located 64 km Northeast of Willits, CA along the I-162 in Mendocino County and is about 22 km from the middle fork of the Eel River. Covelo is located in the Round Valley Indian Reservation and is home to 99 inhabitants (US Census 2000). The test site draws water from the Round Valley Groundwater Basin, which is in the Central Northeastern part of Mendocino County and is about 8 miles long and 4 miles in width. The total capacity of the groundwater basin is about 284×10^6 m^3, and the water is characterized as being a calcium–magnesium bicarbonate type. The TDS typically range between 38 and 116 mg/L, and water can be high in hardness, magnesium, iron, and calcium concentration (EPA, 2016). The typical range in domestic well depths for this area is 9.7–91 m, with an average depth of 30 m. For the groundwater well at the test site, no disinfection treatment was in operation at the time of testing.

Results and discussion

UV dose determination

The results obtained from the laboratory tests are considered first. Table 1 lists the flow rates tested, the percentage UVT for each flow rate, the log10 concentration of MS-2 in the influent and effluent streams, the log10 removal of MS-2 achieved by the system, and the UV dose delivered by the system under these operating conditions. As can be seen in Table 1, the UV dose delivered by the system is significantly higher dose than the 40 mJ/cm^2 of dose >120 or 215.6 mJ/cm^2 assuming continued linearity of dose–response curve. This elevated dose ensures the inactivation of pathogenic bacteria, protozoa, fungi, and viruses. Given the delivered UV dose is more than twice the NSF standard, it may be possible to operate the system with only one of the two lamps and extend the service life of the system (NSF, 2002). Similarly, a lower power UV lamp could also be used, which would lower energy consumption and reduce the cost of materials.

Impact of water quality assessment

To determine the maximum, contaminate load of *E. coli* the system could treat, challenge tests were also performed at UCD using water from Covelo, a campground in the Mokelumne River Canyon, and a campground next to Lake Tahoe. A "challenge test" is when a disinfection system is dosed with a high volume of a microorganism to determine how well the system removes or inactivates the microorganism. The influent characteristics of the source water can influence the penetration of the UV light into the water column and diminish the disinfection performance of the system. Thus, a challenge test to the system is essential to confirm the effectiveness of the system at any particular location. The water quality characteristics from each site are summarized in Table 2.

As shown in Table 3, the minimum log10 removal was 5.9 and it occurred at the Mokelumne River Canyon Campground. However, the average log10 removal from these test was 7.24, which is well beyond requirements from the NSF and USEPA.

Turbidity assessment

Turbidity is a measurement of the number of suspended particles in a water sample. It is an important parameter to quantify in tests of this type because the suspended particles can embed pathogenic microorganisms and thus act as a shield to free floating microorganisms in such a way that prevents these organisms from receiving the required UV dose. Understanding how turbidity impacts the system informs the user on what type of upstream filtration is needed for the system, and serves as a guide for identifying the type of water that can be treated by the UV system. As shown in Table 4, the disinfection capacity of the system was not significantly impacted when tested with water containing turbidity levels from 0 to 18 NTU. In all the samples tested, the disinfection of *E. coli* in all scenarios remained above 5 log10 removal. That this was the case is due to the strong swirl that is imparted to the influent stream. This leads to intense mixing of the flow inside the quartz tube, thereby ensuring that pathogens that may have become attached to suspended particles receive UV radiation as they rotate and tumble towards the outlet. This tolerance to elevated levels of turbidity suggests that the present system would be suitable for operation with upstream filters that have a nominal opening of 20 μm, the size used to screen particles for this analysis. Similarly, the UV system would also be suitable to be operated with waters that contain higher turbidity, such as surface water, sandy groundwater wells, or recycled water.

Field testing

The main concern regarding the quality of the groundwater produced in the well in the Covelo community is fecal coliform contamination, namely *E. coli,* and hence, the subsequent analyses were limited to assessment of the UV system efficacy for bacterial contamination only. The system was powered and operated using a single 100 W solar panel (WindyNation) to demonstrate the system's utility for deployment at off-grid locations.

In order to determine the background microbial concentration for each test, samples were taken from the community's groundwater well at source to be tested for the presence of total coliform and *E. coli*. Results were positive for each round

Table 1. UV dose for the system at various flows and UVTs

FLOW (L/MIN)	UVT (%)	LOG10 INFLUENT MS2 CONC.	LOG10 EFFLUENT MS2 CONC.	LOG10 REMOVAL OF MS2	UV DOSE (MJ/CM^2)
9.46	95	8.18 ± 0.10	1.60 ± 0.12	7.12 ± 0.93	215.6
9.46	70	8.60 ± 0.05	5.59 ± 0.09	3.01 ± 0.09	93.9
12.9	95	8.18 ± 0.10	2.72 ± 0.08	5.46 ± 0.08	173.3
12.9	70	8.60 ± 0.05	6.38 ± 0.13	2.22 ± 0.13	64.5

Table 2. Summary of water quality parameter from each site

ASSESSMENT PARAMETERS	COVELO REC. CENTER AVERAGE	MOKELUMNE CAMP GROUNDWATER AVERAGE	MOKELUMNE CAMP RIVER WATER AVERAGE	MOKELUMNE CAMP POTABLE WATER AVERAGE	TAHOE CAMPSITE #1 AVERAGE	TAHOE CAMPSITE #2 AVERAGE
pH	6.9	7.4	6.62	8.17	6.7	6.61
Turbidity, NTU	2.9	0.25	8.12	1.05	1.52	0.41
Conductivity, μS/cm^2	188.4	535.5	23.05	232.2	118.9	113.4
TDS, ppm	119.7	369.9	14.77	152.6	78.25	74.5
Alkalinity, mg/L	66.7	212	8.9	69	50	53
Calcium, mg/L as $CaCO_3$	23.7	192	8.6	52	25	35
Magnesium, mg/L as $CaCO_3$	15.3	51	11.6	110	15	50
Hardness, as $CaCO_3$ mg/L	39	243	19	162	40	85
UVT, %	99.9	95.5	94.7	95.3	99.4	99.7

Table 3. Summary of results from the *E. coli* challenge tests

SAMPLE	INFLUENT, CFU/100 ML	EFFLUENT, CFU/100 ML	LOG REMOVAL
Covelo Rec. Center	6.00E+09	1.65E+02	7.6
Mokelumne Camp Groundwater	6.00E+09	4.91E+03	6.1
Mokelumne Camp River Water	1.62E+10	0.00E+00	10.2
Mokelumne Camp Potable Groundwater	1.11E+09	1.34E+03	5.9
Tahoe Campsite 1	6.50E+09	3.94E+02	7.2
Tahoe Campsite 2	3.33E+09	1.22E+03	6.4

Table 4. Impact of turbidity on disinfection performance

TURBIDITY (NTU)	LOG10 INFLUENT *E. COLI* CONC.	LOG10 EFFLUENT *E. COLI* CONC.	LOG10 REMOVAL OF *E. COLI*
0.16 ± 0.03	7.17 ± 0.12	1.45 ± 0.17	5.5 ± 0.3
3.53 ± 0.11	7.02 ± 0.16	1.55 ± 1.16	5.1 ± 1.0
6.62 ± 0.21	7.15 ± 0.12	1.24 ± 0.86	5.6 ± 1.0
13.30 ± 0.53	6.91 ± 0.42	0.35 ± 0.49	6.8 ± 0.9
17.83 ± 0.32	6.93 ± 0.06	1.80 ± 0.21	5.1 ± 0.2

Table 5. Bacterial concentration before and after treatment. Results are for groundwater samples collected from the Round Valley Indian Reservation Recreation Center in Covelo, CA

SAMPLE	AVG. TOTAL COLIFORM (MPN/100 ML)	AVG. *E. COLI* (MPN/100 ML)
Outside	68.05	43.3
Kitchen	81.6	44.35
Women's bathroom	145.85	52.85
Post-UV treatment	ND	ND

Note. ND: None detected.

of testing for the sampling period of 8/5/2016–8/7/2016. As per EPA guidelines, results were repeated for confirmation. Additional samples were collected 8/22/2016 and processed 8/24/2016 using IDEXX quanti-trays. The results of these tests are presented in Table 5, which lists the results for each sampling point in the community center. In all the tests performed, the bacterial concentration in the treated water fell to below the detection limit.

In the course of evaluating the UV system's performance in inactivating pathogens, an opportunity arose to evaluate the system's utility in the sense of its adaptability for use in other areas where disinfected water was in demand. This opportunity was provided by the coincidence of the tests there with the presence a team of veterinary surgeons who operated a mobile spay and neuter clinic setup in the community center on temporary basis. The clinic was operated over a period of 48 hr. While no water samples were taken for analysis, it was found that the UV system, due to its compact and robust design, integrated seamlessly into the regular operations of this clinic, primarily as part of the scrubbing-in station where it met the needs for disinfected water pre- and post surgeries.

Cost analysis

At the time of performing this study (May, 2017), the cost of the material (PLA) used in the 3D printing of the key system components was $6.20. The PLA resin was bought in bulk at a cost of $22/kg. The retail price of a 30 W UV lamp was $26.00 though similar lamps, purchased from the manufacturer in bulk, would cost around $7.00/lamp. The cost of the quartz tube was $45.00, while the cost of the PVC pipe that formed the outer casing was $3.00, thereby bringing up the total cost of the unit just under $90.00. An equivalent commercial system having similar flow rate retails at around $600.00 though such systems are fitted by a clock and a UV sensor which was not the case in our system. The lamp manufacturer indicates that the lifetime of the lamp, when operated continuously, is 10,000 hr. The retail cost of electric power for a domestic household is $0.13/kW.hr, and thus, the daily operating cost of this system with 2 30 W UV lamps is just under $0.20 when running at the full capacity of 9.46 L/min, $0.015/m^3. These costs obviously do not include the initial costs of construction and material, or the cost of pumping the water through the system which would be necessary in most cases.

Conclusions

The search for an economic, robust, and practical method for water disinfection in underserved communities is a worthwhile objective considering the great proportion of the world's inhabitants without a safe and secure access to drinking water, and the significant economic hardship that arises due to the consumption of untreated water. In this paper, a novel system for water disinfection with UV light was introduced. The principal components of this system were manufactured using 3D printing—a technology whose costs are decreasing at a fast rate. The system offers many benefits that are not available from commercial systems. Amongst the most significant of these is the avoidance of the problem of lamp fouling and all the complications that arise from it such as the need to install a mechanical wiper that traverses the length of the lamps scraping off residues. The presence of strong swirl in the influent flow ensured that the inner surface of the quartz cylinder remained free of fouling due to the elevated levels of wall shear stress produced by swirl. Moreover, the presence of swirl enhanced the turbulent mixing, thereby ensuring that all pathogens that enter into the system receive the UV dose that is required for their inactivation. Laboratory tests showed that at a flow rate of 9.4 L/min, the system delivered a UV dose of 215 mJ/cm^2 which is sufficient to inactivate most common pathogenic bacteria, viruses, and protozoa. In addition, at the relatively low UVT of 75%, the system delivered a dose of 94 mJ/cm^2 which is also sufficient for inactivation of all common pathogens (USEPA, 2003). Tests performed in situ at a remote and underserved community indicate that the new system, that was powered by a single 100 W solar panel, can be relied upon to provide water that is free from the pathogens of concern. It is hoped that the details provided in this paper can contribute to ongoing efforts directed toward the provision of a sustainable and affordable means for widening access to safe drinking water in underserved communities.

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