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Decentralized UV disinfection systems in rural areas or low-resource contexts: a case study compilation

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Water disinfection using ultraviolet (UV) light is an emerging tool for improving access to safely managed drinking water in rural areas and low-resource regions. However, there is little information comparing existing UV systems in those contexts, towards improving the effectiveness of future UV systems. This work presents 19 case studies of small, decentralized UV water disinfection systems being used during the last 30 years to improve water access. The case studies cover a wide range of project types, including schools, hospitals, communities, households and healthcare facilities, spanning four continents. A variety of energy sources, water sources and social environments are also reviewed. In general, the use of UV immediately improved the microbiological quality of the water; however, long-term tracking of system performance is largely missing. UV system effectiveness was limited by several factors, including the potential for recontamination after UV disinfection, insufficient maintenance, and the absence of regulatory frameworks that allow the more widespread adoption of UV disinfection compared to more conventional disinfectants. This paper is intended to be supporting evidence for the utility of UV technologies for improving safe water access in low-resource settings, and to support practitioners in improving UV system design and implementation.

Water impact

Ultraviolet (UV) light is a promising technology for water and wastewater disinfection in rural and low-resource contexts; however, there is little published information to guide the design of UV installations in those settings. We present 19 decentralized UV disinfection case studies, covering 30 years of implementations across a variety of scales, water sources and geographies, and review the disinfection efficacy, implementation challenges, and future considerations.

Introduction

Access to clean drinking water and sanitation are essential to human health and well-being and were defined as basic human rights by the United Nations in 2010.[1] However, as of 2020, two to 4.4 billion people did not have access to safe drinking water.[2,3] Similarly, although wastewater is one of the primary point-source contaminants polluting freshwater sources, including shallow groundwater sources, over 80% of wastewater worldwide is neither collected nor treated and more than 70% of sewered wastewater from human activities is discharged without pollution control.[3,4] The United Nations Sustainable Development Goals (UN SDGs), which were adopted by all UN member states in 2015, call for bold and transformative steps to address these issues.[5] As many people do not have access to drinking water from an improved water source, available when needed and free from fecal and priority chemical contamination, UN SDG 6 aims to achieve safe and reliable universal access to safe water, sanitation and hygiene (WASH). Improving WASH practices can prevent the 829 000 annual deaths, including 297 000 deaths of children under five years, from diarrhea that results from unsafe drinking water, sanitation and hand hygiene.[6,7] While there has been an increase in access to safely managed sanitation and handwashing facilities with soap and water from 2015 to 2020, progress will need to quadruple to achieve SDG 6 by 2030.[7]

One of the biggest problems directly leading to waterborne diseases caused by bacteria, viruses, and protozoa is the lack of water treatment and, specifically, disinfection. Conventional water treatment approaches emphasize centralized systems, rely

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on intensive capital, and do not address social barriers to water access. Common decentralized water treatment methods implemented at the household or community level include boiling, coagulation and settling, filtration (including biosand filters, ceramic pots, membranes and activated carbon) and disinfection with chemicals such as chlorine.[8,9] Some communities may rely on truck delivery of treated water; however, the transportation tanks often are not adequately cleaned, and deliveries may be unreliable.[10,11] Some areas also face the challenge of satisfying cultural and taste requirements. While the commonly-accepted dose of free residual chlorine is 2.0 mg L^{-1}, taste studies indicate that tolerated chlorine thresholds are lower than this value.[12,13] Additionally, household water storage practices in low- to middle-income countries often result in the recontamination of drinking water after it has been collected,[14–16] reinforcing the case for treatment systems at the point of use. Point-of-use systems for both treatment and storage of water are designed to protect some of the world's most vulnerable populations from preventable waterborne diseases.[17] As the world continues to work toward achieving UN SDG 6 to provide safe water access and sanitation for all, reliable and innovative disinfection has become increasingly important.

After commonly being used for disinfection in centralized systems in high-income contexts, ultraviolet (UV) lamps and UV light emitting diodes (LEDs) have recently emerged as promising alternatives for water and wastewater disinfection in decentralized systems in rural areas and low- to middle-income countries as well. UV disinfection functions as a broad-spectrum antimicrobial agent, effectively inactivating protozoan, bacterial and viral pathogens, without chemical addition or taste and odor challenges, with no harmful effects from overdosing and with little to no disinfection byproduct formation.[18–25] Traditional low-pressure (LP) UV lamps are low-cost, long lasting, and energy-efficient but also are fragile, contain trace levels of mercury, and must typically be left on continuously, whereas UV LEDs can be more expensive, but have a much smaller architecture and have the ability to be instantly turned on and off according to flow, thereby theoretically increasing service life. In recent years, the science of using UV sources for low-cost and remote disinfection applications has steadily advanced. Today, UV technologies are being considered, if not used, in many such contexts around the world.[26–33]

Despite the promise of UV disinfection to help to provide water security to decentralized low-income communities, there are no standard engineering practices nor official protocols to guide the installations. There are also very few published reports on such UV installations in either the peer-reviewed or the grey literature. As such, new installations are currently being designed on an *ad hoc* basis, without addressing the shortcomings or reflecting the strengths of previous installations. The objective of this work is to begin to address this important information gap so that each new generation of UV installations can build on the lessons learned from their predecessors. Nineteen case studies spanning over 30 years are presented, which cover a wide range of projects at multiple scales, including schools, hospitals, communities, households, and healthcare facilities. Moreover, the studies demonstrate the utilization of a variety of UV-based systems with different specifications of flow rates and energy sources, addressing different water sources and social environments, including manually-collected and streamed water from wells, groundwater, rainwater, ponds, rivers, storage tanks and more. The case studies were contributed by researchers, equipment manufacturers, government agencies, and non-governmental organizations, and the contributors were often part of the implementation or management process. Each case study describes the project's background and objectives, the UV technology specifications and, most importantly, the outcomes and lessons learned. In the Conclusion section of this work, cross-cutting considerations for the sustainability of UV systems are summarized across all of the case studies. The Conclusion section also contains an analysis of key aspects of UV water systems, such as water quality impacts and maintenance considerations; as well as future research needs, recommendations for implementation, and implementation challenges that must be overcome. A map (Fig. 1) and database of decentralized UV disinfection systems around the world, containing details about the case studies described in this work, is also available at **https://www.iuva.org/UN-Sustainable-Development-Goals-Task-Force**.[34] It is hoped that this work will serve as a resource for engineers, practitioners, researchers and decision makers who may be working with UV disinfection. Furthermore, it is hoped that it will

This article was written by members of the International Ultraviolet Association United Nations Sustainable Development Goals Task Force. Since 2021, the IUVA UN SDG Task Force has worked to support, and advance, the effective and safe application of UV technologies to protect public health and the environment in low- and middle-income settings. For more information about their work, and to learn about other projects involving decentralized UV disinfection for water and wastewater treatment in low- to middle-income, humanitarian and rural settings around the world, please visit ***http://www.iuva.org****.*

Fig. 1 Map of case study locations highlighted in this paper.

inspire others to report their own experiences with this emerging technology.

Methodology

This paper synthesizes findings from 19 case studies of decentralized UV disinfection systems implemented in rural areas and low-resource settings over the past 30 years (Table 1). The methodology encompasses case study selection, data acquisition, data extraction, and synthesis, designed to provide a comprehensive overview of the practical applications and lessons learned from these projects. The selection of case studies was guided by the objective of compiling a diverse representation of UV disinfection systems in contexts relevant to UN SDG 6, ensuring safe and reliable access to WASH.

Given the limited published literature on this topic, a broad approach was taken to identify relevant projects. The case studies were sourced through the International Ultraviolet Association (IUVA). A "call to action" was disseminated to IUVA members, specifically targeting researchers, equipment manufacturers, government agencies, and non-governmental organizations with direct experience in implementing or managing decentralized UV disinfection projects. This targeted approach leveraged the expertise within the IUVA community to identify a diverse set of relevant case studies. The IUVA network proved instrumental in identifying relevant case studies and connecting with key practitioners. The selection aimed to include a variety of UV system configurations, including both UV mercury vapor lamps and UV LEDs, and systems utilizing different power sources (*e.g.*, grid electricity, and solar power). Additionally, projects addressing different water sources (groundwater, surface water, rainwater, stored water, and wastewater) were prioritized. Case studies contributors included researchers, equipment manufacturers, and non-governmental organizations that were part of the implementation or management process. Case studies were included if they met the following criteria:

1. Technology: the project included the use of a UV water disinfection system, such as mercury-based UV lamps or LEDs.

2. Setting: the work was implemented in a rural area or a low-resource community.

3. Scale: the water treatment system was designed for a decentralized application serving specific populations (*e.g.*, households, schools, communities, hospitals, and healthcare facilities).

4. Documentation: sufficient information was available to extract relevant data regarding system design, system performance, water quality and health outcomes, and system operation.

A standardized approach was then used to extract relevant information from each case study. Key data points included:

1. Project context: location (country, region), community characteristics, and specific needs addressed.

2. Water source: type of water source (groundwater, surface water, rainwater, *etc.*) and its initial quality.

3. UV system specifications: type of UV source (lamp or LED), flow rate, power source, and system design.

4. Operational parameters: operating procedures, maintenance requirements, and challenges encountered.

Table 1 Summary of the case study parameters and findings

Section	Country	Scale	Water source and pretreatment	UV system specifications and performance	Power source and consumption	System controls	Period of operation	UV implementation challenges	Select solutions to implementation challenges
1	Canada	38 LPM System 1: two residences System 2: three residences	**Source:** surface water (creek), concentration of total coliform in raw water was between 100–3000 CFU per 100 mL **Pretreatment:** multi-media filter, two 1 μm cartridge filters	LP UV, VIQUA UV-MAx Pro10, 40 mJ cm^{-2} at 38 LPM, maximum ~3.5 log-inactivation observed for total coliform	Grid power, 120 W, battery provides 1 hour backup power for continuous use	Emergency solenoid shut-off valve in normally closed position, closes when UV dose <40 mJ cm^{-2}, when system loses power, unplugged, or UV lamp not on. Sensor included for monitoring UV intensity	November 2016 – present	Turbidity spikes during spring snowmelt Building community trust	Robust pre-filtration Alarms and back-up electricity source Trained community operators leading operations and maintenance (O&M) Regular community outreach and monitoring
2	Dominican Republic	24 LPM Four primary schools	**Source:** well and harvested rainwater, concentration of *E. coli* in raw rainwater >100 MPN per 100 mL **Pretreatment:** sand filtration, 1 μm cartridge filter	LP UV, Viqua S5Q-PA, ~30 mJ cm^{-2} at 24 LPM, maximum ~2 LI observed for *E. coli*	Solar panels, 30 W consumption by UV system	None specified	2012 – present	Intermittent usage schedule Staff turnover, training, and community awareness Irregular maintenance and testing No sustainable business model	A full-time trained operator and advocate A sustainable business model whereby the systems are implemented and maintained A clear process for the systems to acquire regulatory approval or certification from a locally trusted source
3	India	1.5 LPM Four households	**Source:** Krishna River taps (well or river) RO systems, *E. coli* and total coliform were detected in source water (presence/absence results only) **Pretreatment:** none	280 nm UV LED (Pearl Aqua Micro 6B), design dose was 30 mJ cm^{-2}	Grid power, 9 W consumption by UV LED	None specified	August 2022	Poor supply chain for parts replacement Intermittent electricity Distance from water point means possible recontamination with storage Lack of community awareness and skilled technicians	Designed a tool to promote safe water handling and train analysis by local water ambassadors Diversified electricity sources
4	India	1 L batch reactor One village of 1050 people	**Source:** Oorani – dug out rainwater pond, concentration of *E. coli* in source water	Custom built 275 nm UV LED reactor, ~2.1 LI of *E. coli* observed in field corresponding to UV dose of <5 mJ	Mechanical energy, 6VDC battery	None specified	2018–2020	Funding and local people to be trained for O&M Costs for scale-up of UV LED	Improved awareness of the technology Used pretreatment filters for ooranies with high turbidity

Table 1 *(continued)*

Section	Country	Scale	Water source and pretreatment	UV system specifications and performance	Power source and consumption	System controls	Period of operation	UV implementation challenges	Select solutions to implementation challenges
			133 ± 8 CFU mL^{-1} **Pretreatment:** sand filtration	cm^{-2}, no *E. coli* detected in UV effluent				technology is high	
5	India	15 LPM 500 to 1500 people	**Source:** surface water and groundwater **Pretreatment:** slow-sand filtration	Custom built LP UV, 120 mJ cm^{-2}, maximum 6-LI of *E. coli* observed in laboratory testing dechlorinated tap water	Grid power, 60 W consumption for UV system	None specified	1994–1995	Device flow rate was higher than necessary High cost to develop and transport Lack of sufficient water pressure for UV reactor Rapid chemical and biological fouling Lack of trained personnel for O&M	Reduced size of device to deliver lower flow rates at a lower cost Placed UV lamp above water to reduce fouling Filtration process replaced with slow-sand filter to increase pressure
6	Lao PDR	50 LPM 70 households, maximum of 700 users	**Source:** treated wastewater **Pretreatment:** settler, anaerobic baffled reactor, anaerobic filter, planted gravel filter, aerobic polishing pond	LP UV, 4 Sanitron S50C units in parallel, system designed to achieve at least 30 mJ cm^{-2} at 50 LPM (manufacturer specified 30 mJ cm^{-2} at 75 LPM)	Grid power, 65 W consumption per unit, 260 W total consumption	Guardian digital UV light monitor, detects decrease in UV intensity (*e.g.*, quartz fouling, poor water quality, lamp aging)	2011 – present	Influent water had high turbidity Flow rate exceeded manufacturer recommendations Excessive fouling and scaling of quartz sleeves Irregular O&M	Improved pretreatment and maintenance of wetlands Additional lamps required to increase disinfection capacity Regular sleeve cleaning protocols and O&M
7	Kenya	2.8 LPM One household	**Source:** rainwater **Pretreatment:** biosand and biochar	265 nm UV LED, Klaran WS Series Retrofit Kit, manufacturer specified 4-LI of *Pseudomonas aeruginosa* at 2 LPM	Solar or grid power, 10 W consumption by UV LED	None specified	September 2022–July 2023	Intermittent grid electricity High cost Dirt and bird droppings	Household preferred UV compared to chlorine (taste) Solar panel for consistent electricity
8	Kenya	7.5 LPM Four primary schools (400 people)	**Source:** springwater and rainwater **Pretreatment:** slow-sand filtration	LP UV, VIQUA VT1, manufacturer specified 16 mJ cm^{-2} at 7 LPM, expected dose is <16 mJ cm^{-2} at 7.5 LPM	30 W solar panel, 30 Ah car battery, 12VDC, 9 W consumption by UV lamp	Security boxes requested by schools prevent tampering, window allowed operator to check whether system was on or off	2017–2020	Energy surges leading to lamp burnout Unavailability of local UV systems or parts	Consider the power quality supplying UV Use local UV equipment supplier

Table 1 *(continued)*

Section	Country	Scale	Water source and pretreatment	UV system specifications and performance	Power source and consumption	System controls	Period of operation	UV implementation challenges	Select solutions to implementation challenges
								Lacking skilled operators for water testing, operation, and maintenance	
9	Mexico	5 LPM System 1: 400 households System 2: 187 households	**Source:** spring, well, and rainwater **Pretreatment:** system 1: none System 2: 2 filters (5 μm and 1 μm) and activated carbon	Custom built LP UV, designed to deliver 120 mJ cm^{-2} at 5 LPM	Grid or solar	None specified	First period: 2006–2014, second period: 2018–2022	Behavior change – drinking untreated water Need to subsidize systems with government programs	Human-centered perspective service delivery approach Treatment of water directly into home reduced contamination UV does not impact water taste
10	Nicaragua	5.2 LPM Two communities	**Source:** groundwater, *E. coli* up to 48 MPN per 100 mL detected **Pretreatment:** prefiltration (100, 10 μm, and 5 μm), reverse osmosis	LP UV, VIQUA VT4, designed to deliver 40 mJ cm^{-2} at 5.2 LPM	Diesel generator, 20 W consumption by UV system	None specified	2018–2022; not constructed	Unavailability of local UV systems or parts Political tensions Lack of community buy-in Intermittent electricity, 8 hours per day	Emphasize community buy-in and communication Maintain relationships with local communities and NGOs
11	Philippines	2 LPM One community	**Source:** groundwater, *E. coli* up to 5000 MPN per 100 mL detected **Pretreatment:** none	280 nm UV LED, no dose specified	150 W solar panel, 12 V, 350 mA	None specified	September 2018 – present	Potential photoreactivation of microorganisms Seasonal variation of water quality Insufficient microbial inactivation	Solar power as a suitable, alternative power source Increase contact time, number of LEDs Reduce exposure to sun for photoreactivation Disinfection of storage tank
12	Rwanda	5 LPM 23 schools and small hospitals	**Source:** rainwater **Pretreatment:** two washable bag filters of 25 μm and 10 μm	LP UV, 40 mJ cm^{-2} at 5 LPM	80 W solar panel or 12 V car battery	None specified	2010 – present	Sustainable financing of units and maintenance Local attendance for installation, maintenance, service, and education	Schools prefer UV due to lower costs and less maintenance

Table 1 *(continued)*

Section	Country	Scale	Water source and pretreatment	UV system specifications and performance	Power source and consumption	System controls	Period of operation	UV implementation challenges	Select solutions to implementation challenges
13	Rwanda	10 LPM Two communities	**Source:** piped water, rainwater, and surface water, up to 63 CFU mL^{-1} detected in field **Pretreatment:** gravel filter with self-filling tank for filter back wash, and pressurized sand filter	LP UV, up to 1.8-LI achieved (no microorganism specified), no dose specified	50 W or 102 W solar panel	Sensor and alarm system notify operators of faulty lamp	2005–2015; maintained and operated for at least 10 years by Engineers without Borders – USA	Community adoption of UV Unavailability of local UV systems or parts Training of local personnel to operate system	Coupling system with other technologies – drip irrigation, lighting, biogas generators Strong relationships with community leaders enabled recruitment and training Liaising with importers for UV lamps Free-of-charge system was a component in adoption
14	Rwanda	Up to 100 LPM One community	**Source:** piped water, rainwater, and surface water **Pretreatment:** elevated backwash tank, gravel filter and pressurized sand filter	LP UV, 2 Sterilight UV systems, dose not specified	Solar panels	System includes RealTech UV-transmittance sensor, flowmeter, and control valve. UV lamp operation controlled by flow monitoring system	2007–2010	Installation required extensive engineering and project management Funding through weak carbon credit markets not a sustainable business model to provide sufficient revenue for O&M	Consider ultrafiltration pretreatment Future potential for sustainable financing through carbon finance as market develops
15	South Africa	15 LPM Two communities	**Source:** surface water and groundwater **Pretreatment:** none	LP UV, maximum 6-LI of *E. coli* observed in laboratory testing dechlorinated tap water	Grid power, 60 W	Photosensor for monitoring the UV lamp and sensor for UVT controlled flow	1997	User O&M Public sector mobilization and financing	Simplify systems to reduce maintenance requirements Flow control valve opening when UV system is supplied with power to reduce human error Two photo sensors control valve to open when UV is on and UV transmittance is high

Table 1 *(continued)*

Section	Country	Scale	Water source and pretreatment	UV system specifications and performance	Power source and consumption	System controls	Period of operation	UV implementation challenges	Select solutions to implementation challenges
16	Tanzania	5 LPM Seven systems at six healthcare facilities	**Source:** rainwater **Pretreatment:** first flush, sedimentation	LP UV (unspecified system)	125 W solar panel (12 V) charging 12 V battery, 25 W consumed	None specified	2019 – present	Lamp burnout and damaged electrical wires and components Poor user-focused design: difficult to inspect and clean system and UV lamps Poor cleaning of rainwater harvesting system and quartz sleeve led to significant fouling	Improve operation, maintenance and inspection protocols Training of community operators UV reactor and hardware must be enclosed from environmental factors
17	Uganda	3.5 LPM One healthcare center and one primary school	**Source:** rainwater and groundwater, *E. coli* too numerous to count, reduced to 104 CFU per 100 mL by filter **Pretreatment:** biofiltration cartridge filters	280 nm UV LED, PearlAqua Automate System, UV dose not specified	Solar or grid, 20 W consumption for UV LED system	Flow meter for detecting flow, alert system for faulty UV LEDs	2021 – present	Protecting the UV system from damage Inconsistent power supply and potential power surges User safety	UV must be enclosed for protection Integrate UV LED units into micro-factories to treat great volumes of water
18	United States & Ukraine	38 LPM Deployed in several locations	**Source:** piped water or surface water **Pretreatment:** activated carbon filtration	280 nm UV LED (Pearl Aqua Deca), estimated 30–40 mJ cm^{-2} at 45 LPM at up to 38 LPM	Generator or grid, 180 W consumption for UV LED system	None specified	2021 – present	Awareness, knowledge, acceptance at government level	Better integration into existing emergency protocols of government
19	United States	0.5 LPM 300 people	**Source:** surface water, total coliform concentration up to 325 CFU mL^{-1} and *E. coli* concentration up to 7 CFU mL^{-1} **Pretreatment:** slow-sand filtration, total coliform up to 10 CFU mL^{-1} and *E. coli* up to 2 CFU mL^{-1} in filter effluent	UV LED (Pearl Aqua Model 25G), challenge testing with MS2 achieved RED >40 mJ cm^{-2} at 0.5 LPM	Grid, 26 W nominal power consumption	Indicator lights included for status of UV LEDs. Internal current loop – measures lamp life	January 2017–February 2018, Pilot Study	Temporal changes in UV transmittance and flowrate	UV LEDs useful with low mineral water to minimize fouling, reduce chlorine use, and minimize formation of disinfection byproducts

LP = low-pressure. LI = log inactivation.

5. Performance data: pre- and post-disinfection water quality data (*e.g.*, indicator organism concentrations, turbidity), where available.

6. Lessons learned: key insights, challenges, and recommendations from the project implementers.

This review is subject to certain limitations. The case studies represent a non-random sample of projects, and the availability of data varied across cases. Due to the nature of field implementations and the nascence of decentralized UV disinfection, rigorous control groups and comprehensive monitoring data were often lacking. The reliance on self-reported data and project reports may introduce biases. Despite these limitations, this review provides a valuable synthesis of practical experiences with decentralized UV disinfection systems, offering insights for improving future implementations and advancing progress toward SDG 6.

1. Point-of-entry UV disinfection in an Indigenous community in British Columbia (Canada)

1.1. General data

Type of Project	Point-of-Entry UV disinfection
Location	British Columbia, Canada
Project Period	November 2016 to Present
Scale	Two small remote communities (five houses), 38 LPM
Affiliation & Contact	RESEAU Centre for Mobilizing Innovation (www.reseaucmi.org) Prof. Madjid Mohseni, madjid.mohseni@ubc.ca
UV System	Low-pressure UV, VIQUA UVMax Pro 10
Implementation Challenges for UV	• Surface water (creek source), with turbidity spikes during the spring snowmelt • Requirement to gain the trust of the community on the proposed solution
Select Solutions to Implementation Challenges	• Robust pre-filtration with a multi-media filter, 1-micron nominal cartridge filtration, and 1-micron absolute cartridge filtration • Alarms and back-up electricity source • Regular community outreach and monitoring • Trained community operators to oversee operations and maintenance (O&M)

1.2. Background

Lytton First Nation is located in the Fraser Canyon, approximately three hours northeast of Vancouver, British Columbia, Canada. The Nation consists of 56 reserves, spread over 14 161 acres of land, and split by the Fraser River. Though rich in natural resources, the Nation is challenged by the relative remoteness of their individual communities. A decade-long struggle with water advisories led to a community-backed initiative to seek alternative solutions. RESEAU Centre for Mobilizing Innovation (RESEAU CMI) was engaged to provide an innovative solution for two reserves located far from the larger communities within Lytton, which did not qualify for funding of a centralized water system from Indigenous Services Canada (ISC).

IR3 (Spintlum) and IR11 (Yawaucht) consisting of two and three residences, respectively, are supplied by surface creek water, and were on long-standing boil water advisories. Following a course of feasibility work, design, community engagement and site visits, the point-of-entry (POE) pilot project was introduced. Using water quality data collected by the RESEAU team, the project partners designed POE systems to properly treat each community's water source. In this case, both IR3 and IR11 faced significant levels of DOC, turbidity, total coliform, and *E. coli* counts. All POE systems were designed to each treat water for a single residence. The general characteristics were determined following a thorough sampling program. The results for turbidity, total coliform and *E. coli* are shown in Table 2 as compared to Health Canada's Guidelines for Canadian Drinking Water Quality.[35] Turbidity was measured using a Hach colorimeter at the University of British Columbia.[36] Total coliform and *E. coli* were measured by the First Nation Health Authority with the IDEXX MPN method, following the 9223 enzyme substrate coliform test in the Standard Methods for the Analysis of Water and Wastewater.[36]

1.3. Community consultation and technical description

The community consultation and site visits were early priorities for the POE project. It focused on understanding site characteristics, presenting the project to residents, and gauging homeowner interest and willingness to participate. In order to effectively plan for these initial steps, it was established early on that a POE pilot project in first nation communities would be closely managed by the participant first nation itself, with operation by trained water treatment operators and not homeowners themselves.

Over the course of preliminary meetings and site visits, the project was successfully introduced. The engagement sessions provided an opportunity for knowledge sharing, but most importantly gave community members a chance to give input and have their questions addressed. One of the key

Table 2 IR3 and IR 11 raw water data

Parameter	Unit	Guideline value[a]	IR11	IR3
Turbidity	NTU	≤ 0.3[b]	3.68	0.32
Total coliform	CFU per 100 mL	0 per 100 mL	271	741
E. coli	CFU per 100 mL	0 per 100 mL	<1 to 20	<1 to 5

[a] From the Guidelines for Canadian Drinking Water Quality (February 2017).[35] [b] Treatment limits for individual filters or units: less than or equal to 0.3 NTU in at least 95% of measurements either per filter cycle or per month; never to exceed 1.0 NTU.

requirements to a successful POE system is an established trust by resident users, and First Nations Health Authority (FNHA) was engaged in the site visits to help mitigate concerns.

On the technical side of the project, the design requirements for POE treatment in IR 3 and IR 11 were established with adherence to Health Canada's Guidelines for Canadian Drinking Water Quality (GCDWQ), ISC Decentralized Protocol, and Occupational Health and Safety Requirements.[35] A process flow diagram of the treatment system is in Fig. 2. The entire treatment system, at each location, was contained within a locked enclosure accessible only by the operator. In general, incoming raw water was subject to turbidity reduction media, 1-micron nominal cartridge filtration, 1 micron absolute cartridge filtration, followed by UV disinfection.

Fig. 3 The Lytton POE systems, with the low-pressure UV system, were installed in a secured enclosure, placed inside residents' homes.

1.4. Technology description

A VIQUA UV-Max Pro10 low-pressure UV lamp was used to achieve the required inactivation of microorganisms. This system is Class A certified by NSF/ANSI 55 (the Public Health and Safety Organization American National Standard 55) and is able to provide a UV dose of at least 40 mJ cm^{-2}, at a flow rate of up to 38 liter per min (LPM). The unit consumes 120 W at either 120 V or 230 V. The system (Fig. 3) also included a cooling fan which was on at all times, and the UV lamp was on at full intensity if water was flowing; the lamp dimmed only if water was not flowing for several minutes. For operation and maintenance, homeowners were given a protocol with instructions to flush the system for 3–5 minutes after the lamp startup period, when the water was required for drinking. A drain was used during UV system maintenance, such as cleaning the UV sleeve.

An emergency solenoid shut-off valve was located downstream of the UV lamp and was normally closed when the water was not in use, preventing water from reaching the consumer. It also closed if the UV dose was less than 40 mJ cm^{-2} and if the system lost power, was unplugged or if the UV lamp failed to turn on. In response to a power failure, the solenoid valve would close, as it would no longer be powered open. The UV unit had a sensor to detect lamp intensity. If a safe UV dose was not achieved during the warmup cycle (if the intensity went below a set value calculated for the required dose), an alarm occurred, and the solenoid remained closed. A backup battery was available for temporary power (approximately providing up to one hour power for continuous operation) in the case of a power failure.

1.5. Performance monitoring

In November 2016, RES'EAU worked with the Lytton Operations and Maintenance department to install and commission the POE units in each home site. With the on-site assistance of the manufacturer, the process commissioning allowed for efficient troubleshooting and an opportunity for each operator to program a unit with one-on-one assistance.

Following the established protocol for regular and successive water testing, the first five weeks of piloting included a frequent sampling schedule. This was necessary to thoroughly assess the system performance and provide

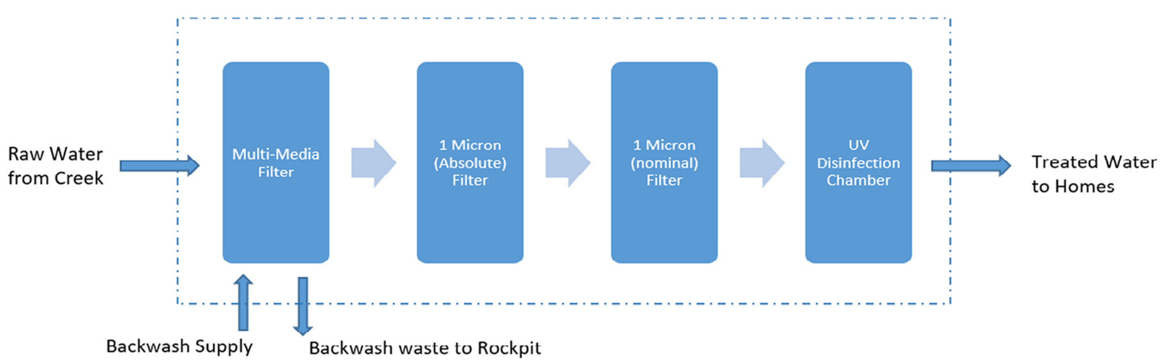

Fig. 2 The Lytton POE systems process flow diagram.

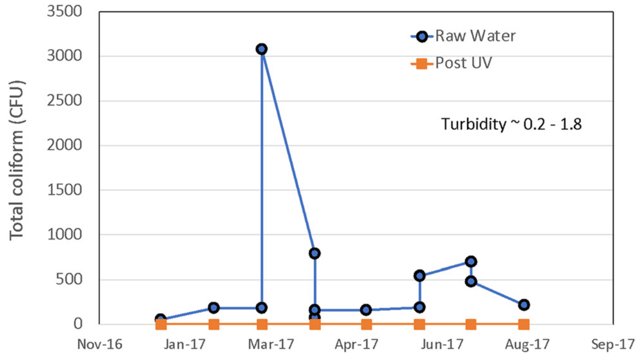

Fig. 4 Total coliform counts, before and after the UV POE systems.

careful oversight. The regulations set by FNHA required three consecutive weeks of clean results (*i.e.*, non-detectable microbial counts) in order to lift the boil water advisories. This target was achieved between mid-December and mid-January 2016, based on a staggered sampling schedule and testing that included weekly bacteriological results. As of January 2017, both Reserve communities and all five participant residences, were off the boil water advisory.

As the project progressed through the first year of installation, the water quality sampling frequency moved to a bi-weekly schedule (Fig. 4). Despite spikes in total coliform counts, which coincided with spikes in turbidity, the bacteria were completely inactivated by the UV light. A number of formal and informal engagement sessions were coordinated, both in the community and *via* conference calls with the purpose being to facilitate regular communication between the project partners, gather community feedback, and develop strategies to any arising issues. Ongoing follow-up work to assess the operator and resident satisfaction, as well as monitoring system performance and O&M costs, continued throughout the pilot year.

Over eight years later, the system is still in operation. No issues have been reported. Periodic maintenance includes UV lamp replacement and quartz sleeve cleaning approximately every six months.

1.6. Lessons learned

Monthly assessments, completed by operators and homeowners, helped to ensure the project met local expectations. Following the end of the pilot year, and upon detailed analysis of the performance data as well as community feedback, the homeowners and the community administrators agreed to continue operating the system as a permanent solution. Surveys of community members on the POE solution showed that 100% of the eight people surveyed (75% strongly agree, 25% agree) would want a POE solution for permanent water treatment in the community and that all agreed there had been minimal issues with the POE (75% agree, 25% strongly agree).[37]

2. Provision of safe water access in rural cities of the Dominican Republic

2.1. General data

Type of Project
Potable water treatment

Location
La Vega, Dominican Republic

Project Period
2012 to Present

Scale
Four primary schools, each having a 24 LPM system

Affiliation & Contact
Purdue University, Division of Environmental and Ecological Engineering and Lyles School of Civil Engineering
Rachel E. Gehr, rgehr@purdue.edu
Dr. Ernest R. Blatchley III, blatch@purdue.edu

UV System
Low-pressure UV, VIQUA S5Q-PA

Implementation Challenges for UV
- As the system was installed in a primary school, the academic calendar resulted in the system being abandoned during the summer
- Operator turnover and lack of experience
- Certification of system by local labs
- Lack of communication from local partners, need a full-time person to monitor systems

Select Solutions to Implementation Challenges
- A full-time trained operator and advocate to keep the systems running
- A sustainable business model whereby the systems are implemented and maintained
- A clear process for the systems to acquire regulatory approval or certification from a locally trusted source.

2.2. Background

In direct correlation with the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation), a course was developed at Purdue University to provide safe water access in rural areas of the Dominican Republic. The project team comprises undergraduate and graduate students primarily studying engineering, nursing and agriculture. Students work within four committees – design; communications; sustainability; and monitoring, evaluation and publication (MEP) – to provide community-scale potable water treatment systems; administer WASH education; prepare a long-term plan for the systems; and survey the local community on attitudes toward public health practices, respectively.

Since its launch in 2012, the Water Supply course has implemented drinking water treatment systems in four primary schools within the La Vega region of the Dominican Republic. These schools are all located within 10 minutes of one another and often collaborate or work together. Although the COVID-19 pandemic delayed project goals, there are plans to implement a fifth system in the community of Desecho. While this small town lies on a beautiful mountainside, its increased elevation has made it difficult for the town to acquire basic resources, particularly during the rainy season. It is the community in greatest need of potable water and may be provided with both a well and a treatment system for harvested rainwater to satisfy the town's daily water requirements.

2.3. Technology description

The current source of drinking, cooking and cleaning water in these communities is untreated rainwater. The implemented treatment systems (Fig. 5) include two forms of

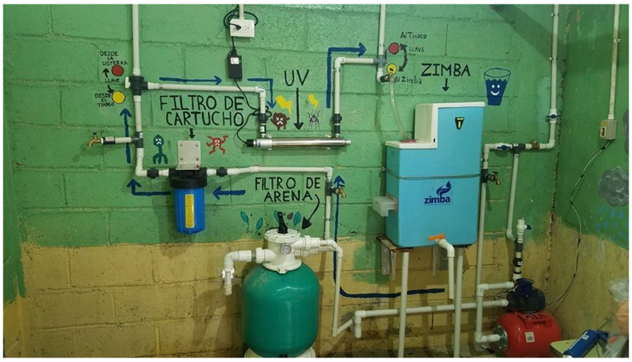

Fig. 5 Potable water treatment system installed in Escuela Primaria Aureliano El Mamey.

filtration and disinfection to produce finished water that is safe for drinking, cleaning and cooking at the schools. Treated water also can be routed to the handwashing station (Fig. 6). A sand filter is used to remove debris and large particles followed by a 1-micron cartridge filter for removal of microscopic particles, including bacteria and other microbial pathogens.

Primary and secondary disinfection provided a multi-barrier treatment system for the communities. A UV disinfection system inactivates microbial pathogens, including bacteria, viruses and protozoa, and serves as the primary disinfectant. The VIQUA S5Q-PA unit was selected as an off-the-shelf point-of-use system that would meet the target flow of 24 LPM for delivering at least 40 mJ cm^{-2}. The UV system includes a sensor on the reactor to indicate operation as well as a Sterilight Silver series ballast with a large LCD display that indicates the remaining life of the UV lamp. Zimba (the blue unit on the right of Fig. 5), an autonomous, gravity-based batch chlorinator, dilutes bleach

Fig. 6 Handwashing station at Escuela Primaria La Torre with handprints from the school's students.

(*i.e.*, sodium hypochlorite) to the desired concentration (unspecified), which provides secondary disinfection during transportation and storage. The Zimba could chlorinate roughly 10 L per batch.

The systems deliver an average of 24 LPM and are powered by solar panels, which were installed by local trade specialists hired by the team. The solar panel system included a DC–AC converter and battery system. Once installed, the school's designated operator was provided in-person training by Purdue engineering students, a manual written by native Spanish speakers and videos addressing maintenance and troubleshooting. Custom manuals were written for each system and included simple explanations of each component's purpose, manufacturer, price, O&M. Schools were provided with compartment bag tests for *E. coli*, test strips for free and total chlorine, a UV transmittance (UVT) meter and a probe that measures pH and total dissolved solids (TDS), as well as a turbidimeter that is shared among the four schools. The water treatment system is still used intermittently and the solar panels are used consistently by the school.

2.4. Challenges and opportunities

Treating the rainwater to a potable quality was the easiest of the encountered challenges (Table 3). The greatest barrier to project success perhaps lies within the choice of installing these systems in elementary schools. Although they are central to the communities both socially and geographically, the academic calendar leaves the systems unused during summer and winter breaks. This lack of operation often results in equipment failure, requiring maintenance or replacement. Operators who know how to resolve these issues often change due to school staff turnover, but new operators are not sufficiently trained after accepting the role. Parents of the schoolchildren have obtained the required certifications from Dominican labs proving the water's potability, but these labs are difficult to find in-country. Finally, no sustainable business model has been developed due to the complication that water cannot be sold from school property. These problems may all be solved by having a Dominican-native employee to monitor all installed systems year-round, perform maintenance, conduct water quality testing and communicate with Purdue.

2.5. Lessons learned

While the engineering portion of the project was relatively easy to design and implement, it will not be successful without

Table 3 Water quality data for raw and treated rainwater

Parameter	Raw rainwater	Treated water
Turbidity	8.10	1.18
Total dissolved solids (TDS)	86.8 ppm	63.2 ppm
UV transmittance (UVT)	82%	92%
E. Coli Most probable number (MPN)	>100/100 mL	0/100 mL

trust from community members and year-round use and maintenance. The systems require regular operation and water quality testing to ensure each component is working properly. This can be achieved with the support of a full-time operator who oversees the four locations and communicates with the Purdue team. Before this project can be implemented in other regions of the Dominican Republic, the project must gain community investment in the importance of potable water and commitment to operating the system on a daily basis.

3. Demonstration of a UV LED water treatment system for rural areas in South India

3.1. General data

Type of Project Pre-implementation field-testing of a new UV LED solution built for rural areas
Location South India, Karnataka State
Project Period August 2022
Scale The village population includes 650 households and approximately 2,600 people.
Affiliation & Contact The Water-Energy Lab at Tel Aviv University Dr. Dana Pousty, dana.poustylakritz@colorado.edu Prof. Hadas Mamane, hadasmg@tauex.tau.ac.il
UV System UV LED, 275 nm, PearlAqua Micro 6A, AquiSense Technologies
Implementation Challenges for UV • Poor supply chain for parts replacement • Intermittent electricity • Distance from the water source means possible recontamination with storage • Lack of community awareness of WASH practices and lack of skilled technicians
Select Solutions to Implementation Challenges • Designed a tool to promote safe water handling and train analysis by local water ambassadors • Diversified electricity sources

3.2. Background

Located in rural India in Karnataka state, the area comprises 650 households and approximately 3600 people in remote villages with intermittent electricity and a water stream. Water sources include direct from the main river (Krishna River), community taps for each group of four households including hand pumps (streamed from the river or wells), and long walking-distance reverse osmosis (RO) paid filter plants, with a water cost of 5 Rupees per 20 L. The water generally is collected manually and stored for a long time in unmaintained water containers in different structures and materials, which usually are contaminated with *E. coli*, total coliforms and river particles.

Community taps are scattered throughout the village within the living area, with a group of four households living around a tap in the village. The water is not streamed regularly; instead, it is streamed without notice between 4:00 a.m. and 7:00 am (Fig. 7). The water quality is poor and the source of the water is the river or wells. Table 4 details the water quality with high total dissolved solids, TDS, and part of the sources with high turbidity. The water quality at the current taps is also poor. Structurally, the taps are shaky, fragile and unstable; thus, the community must exercise care to avoid damaging them. The water pressure when the tap is open ranges from 0.3 to 0.8 bar, and when the taps are closed the pressure ranges from 1.0 to 1.5 bar. The inner tap diameter is between 1.6 cm and 2.2 cm, and the outer tap diameter is between 1.8 cm and 2.6 cm. For hand pumps, the inner diameter is 4.6 cm and the outer diameter is 5.0 cm (Table 4).

3.3. Technology description

The flow-through module used contains a single 275 nm LED based on a Micro 6A AquiSense reactor. The system has a hydraulic retention time of 2.0 s and was designed to disinfect flowing water up to 2.0 LPM. In this case, the flow rate was 1.5 LPM and the design UV dose at this flow rate was 30 mJ cm^{-2}. The UV LED was powered by the grid line electricity system, which requires an input voltage of 11–14 V.

To obtain bacterial presence or absence for the water source examined, the samples were kept in a custom-built field incubator under conditions that are suitable in terms of

Fig. 7 Community water taps.

Table 4 Chemical water source parameters

			Hach					Sensors					
Source type	Inner diameter (cm)	Outer diameter (cm)	Free chlorine	Total chlorine	Total hardness (ppm)	Total alkalinity (ppm)	pH	Temp (C)	Conductivity (ms cm^{-1})	TDS (ppm)	Turbidity (NTU)	OD (mg L^{-1})	ORP
Control – Mineral water	—[b]	—	0	0	0	0	6.2	29	0	0	0	7.72	0
RO filter	2.4	2.6	0	0	50	40	6.2	28.6	0.3	267.2	0	7.34	146
HH[a] RO	—	—	0	0	50	0	6.8	28.7	2.1	683	0	7.36	153
Community tap #1	1.6	1.8	0	0	425	240	7.8	28.1	0.3	195	0	7	158
Chief HH[a]	2	2.2	0	0	245	180	8.4	28	2.2	871.5	0	6.9	135
Handpump	4.6	5	0	0	425	240	8.4	29.3	2.4	924	8.6	6.9	140
Community tap #2	1.6	1.8	0	0	250	120	7.8	29.7	0.3	209	118	7.3	160
Community tap #3	1.9	2.2	0	0	250	240	8.4	28.4	0.3	201.3	46	7.1	159
Krishna river	—	—	0	0	250	120	8.4	28.5	1.92	1036	124	6.32	—

[a] HH = household. [b] Not applicable.

duration and temperature, namely 31° to 37 °C for 24 h, which can allow the bacteria to develop and reproduce. The incubator is easy to use, cost-effective and purposely built for rural areas with intermittent electricity supply. The parts of the incubator were purchased in India and built in the field. Fig. 8 shows the field incubator and the Aquagenx field test

Fig. 8 Field incubator and test kits.

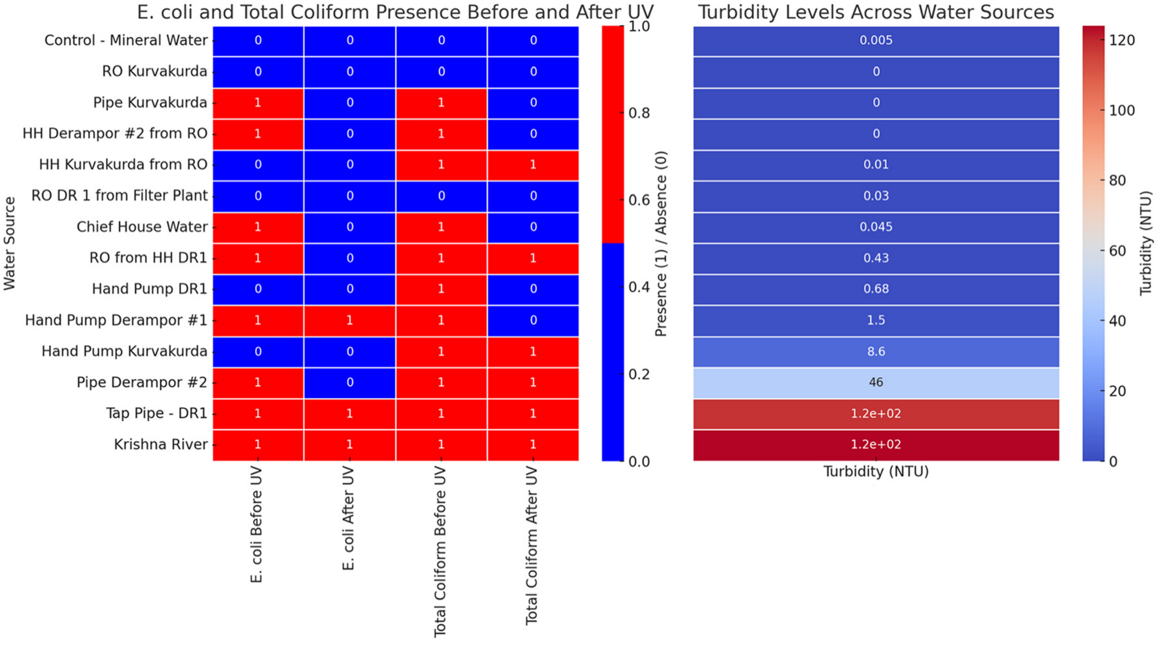

Fig. 9 E. coli and total coliform results before and after UV disinfection, and turbidity levels across water sources.

before incubation. *E. coli* and total coliform results are shown in Fig. 9.

3.4. Challenges and opportunities

The UV transmittance of water is critical to ensuring an adequate UV dose is being applied. However, measuring UVT in the field is challenging and, therefore, we do not have UVT data. In addition, we found that the turbidity and TDS levels vary between the water sources and containers, which must be considered while using UV technology for disinfection.

Moreover, the awareness of sanitation standards is low. For example, the water in the household is commonly stored in water containers that are placed on the floor, are not often cleaned, can be not covered at all, *etc.* We conducted detailed social surveys from each household to map and identify the behavior and awareness.[38] The challenge was to provide a solution that is suitable for the household-level needs, considering the drinking water consumption, electricity hours and the village's social standards. This solution aims to overcome the challenges by providing a point-of-use, affordable and easy-to-use solution that will be integrated into the water tanks, which will be activated by an alternative energy source.

3.5. Lessons learned

The lessons learned (or recommendations for future work) are as follows:

- Consider the entire water journey from source to use. The water sources are not always the problem, as even treated water can get re-contaminated during storage.
- Water should be treated as close as possible to the point of use. The water disinfection process should not be placed at a distance (too much effort for daily use); instead, it should be in a close community tap or at the household level.
- Rely only on the existing energy sources. Solar panels are difficult to install, maintain and operate in these areas; thus, energy harvesting could be from diversified options which are case specific, such as a hydrogenator or a battery.
- Count on intermittent electricity each day. The system cannot be dependent on constant electricity supply but can be based on short-term charged electricity.

3.6. Acknowledgements

The authors thank Mr. Igor Donskoy and Assaf Cohen from School of Mechanical Engineering, Tel Aviv University; Reshma Ramesh and Prof. Bhavani Rao from Center for Women's Empowerment and Gender Equality; Amrita Vishwa Vidyapeetham, Amritapuri, India; Dr. Ram Fishman from Department of Public Policy; Faculty of Social Sciences, Tel Aviv University, Israel; and Amit Porat and Nethanel Rachel for developing the field incubator.

4. Improvement of drinking water quality from surface water ponds with a zero-energy UV LED reactor (South India)

4.1. General data

Type of Project Drinking water
Location Pattikadu village, located in Tirukalukundram Block of Kancheepuram district in Tamil Nadu, South India
Project Period 2018 to 2020
Scale The total geographical area is around 294 hectares, with a total population of 1,050 people in one village.
Affiliation & Contact Research: Center for Environmental Studies, Anna University, Chennai, Tamil Nadu, India Prof. S. Kanmani, skanmani@annauniv.edu
UV System UV LED, 275 ± 5 nm
Implementation Challenges for UV • No local UV LED manufacturers in India • Costs for scale-up
Select Solutions to Implementation Challenges • Improved awareness of the technology • Used pretreatment filters for ooranies with high turbidity

4.2. Background

It is common in Tamil Nadu in India for communities to obtain their water from oorani; a Tamil name for a dug-out pond that traps rainwater run-off and stores it for further use. Ooranies are formed in rural areas where groundwater is either inadequate or unfit for further use.

With the advent of bore wells, hand pumps, and Community Water Supply Systems (CWSS), ooranies took a back seat and were left without proper care. Due to sparse rainfall and the fast depletion of groundwater, the drinking water supply available through the modern systems in rural areas faced problems. At this juncture, the Secretary to Government, Rural Development Department considered it expedient to renovate the ooranies not only to ensure sustainable water for drinking but also to support the existing bore wells and CWSS. The Secretary of the Government of Tamil Nadu decided to form a task force to renovate the ooranies in a scientific manner to ensure sustainability with people's participation.

The Center for Environmental Studies, Anna University – along with the Ministry of Rural Development – had come forward with an aim to provide clean and safe drinking water for the rural people. In order to achieve drinking water quality for zero coliforms, disinfection studies had to be conducted using UV LED disinfection. For executing the research work, Pattikaddu Oorani (Tamil Nadu, South India) was selected, where oorani is the only source of drinking water for the residents (Fig. 10). Thus, the objective was to disinfect drinking water taken from an oorani at the end-user stage in the rural villages using a zero-energy reactor system for disinfection in rural areas, where a hand pump is the major point-of-use for the small community population.

Fig. 10 Pattikadu Oorani.

4.3. Technology description

For the improvement of the quality of drinking water, zero-energy technology for the removal of pathogenic organisms was developed (Fig. 11) as described further in Sundar and Kanmani.[39] An annular UV LED photoreactor (1.0 L capacity) designed as a batch reactor that contained 24 UV LEDs connected in parallel and placed inside a quartz tube of diameter 30 mm and length 300 mm. The quartz tube was fitted inside an enclosure made of stainless steel of diameter 87 mm and length 240 mm and thickness 2.0 mm. The distance between the light source and the nearer/farther side of the water medium was 1.5 cm and 2.75 cm, respectively.

The hand lever of a hand pump was welded with the necessary support angles at appropriate places to achieve the full rotation of the circular plate, where the plate rotates with the mechanical up and down movement of the hand lever. The circular plate was connected to the large gear wheel, which was connected to the dynamo through a small gear wheel. One rotation of the larger gear wheel induces the smaller gear to rotate 10 times. On average, in one minute, 60 strokes (up and down movement of the lever) can be generated by a person. The mechanical energy of the gear wheel was converted into electrical energy through a dynamo. The dynamo was connected to the 6 V DC battery through a bridge rectifier. The voltage generated by the hand pump lever produced 600 revolutions per minute in the small gear wheel, which was enough to charge a 6 V battery.

E. coli concentrations were measured using the pour plate method, which involved adding 1 mL of the sample to 20 mL of nutrient agar in sterile Petri dishes and mixing, solidifying, and incubating at 30 °C for three days before colony counting (IS 14648:2011). The initial colony count was 133 ± 8 CFU mL^{-1} *E. coli* inactivation of 100% was observed in six minutes of disinfection time in the UV LED batch annular reactor fitted with the hand pump.

Fig. 11 Fitting of experimental setup on Pattikadu Oorani. The hand pump with gear wheel, shown on the left, was modified to drive a gear system linked to a dynamo, converting mechanical energy into electricity and charging a 6 V DC battery. The UV LED reactor is the silver cylinder in the bottom right of the right photo.

With the exposure to UV LED irradiance, the colony counts reduced significantly with time, resulting in <1 CFU mL^{-1}. The system was observed to achieve a maximum inactivating fluence of ~5 mJ cm^{-2} for *E. coli*, which corresponds with 2 log inactivation. The cost of UV LEDs is the major barrier to scalability, followed by the design and large-scale manufacturing of UV LEDs through collaboration with manufacturing companies with a target of zero-energy disinfection technology at the point of use in remote rural villages.

4.4. Challenges and opportunities

Oorani systems have been in existence for hundreds of years. The traditional system provided water without filtration. Turbidity has been removed by using gypsum or natural seeds, which function as flocculants. With the technical development in rural areas, emerging pollutants such as synthetic fertilizers, pesticides and aromatic hydrocarbons entered the supply chain of Ooranies. In many cases, Ooranies became polluted and were neglected. These ponds have a sand filtration system for turbidity removal, but the bacteriological quality of these ponds is not under compliance, in most cases. Boundary conditions for the design filters are low technology, low cost and low maintenance. In the design of the UV LED photoreactor, 70% to 80% of the total capital cost was utilized for UV LEDs, and there are no local UV LED manufacturers in India.

4.5. Lessons learned

Disinfection using UV LEDs offers numerous advantages, including the robustness of the solid-state technology, typically low cost, long lifetime, low heat generation and small size compatible with modern trends in miniaturized instrumentation. The electrical power required for the disinfection was taken from the mechanical energy from the up and down movement of the hand pump lever, which would be a zero-energy technology for practical applicability for the improvement of drinking water quality. Even though this technology was developed for the rural sector, it could be extended to semi-urban, urban and industrial communities either at the household level or at the field-scale level for water purification. In the future, the reactor may be evaluated for higher throughput with other UV disinfection methods, including UVA/UVC combined treatment, UVA/TiO_2 photo-catalytic disinfection or pulsed UV disinfection.

The novelty of the study is its practical applicability of a sustainable point-of-use disinfection technology that might be economically implemented in lower-income, smaller communities. Therefore, an economically feasible and self-sustaining disinfection system is required, which is the reason the wavelength ~280 nm was chosen for the present study.

5. UV waterworks: water disinfection for rural India

5.1. General data

Type of Project Drinking water from a local stream that is naturally contaminated with raw sewage leachate from old leaking underground sewer pipes
Location The UV Waterworks project began at a trial scale in California, United States, before installing onsite at several sites in India, including at Bhupalpur.
Project Period 1994 to 1995
Scale Initially 60 LPM, scaled down to 15 LPM, enough for 500 to 1,500 people
Affiliation & Contact Energy Technologies Area, Lawrence Berkeley National Laboratory and University of California Berkeley Prof. Ashok Gadgil, ajgadgil@lbl.gov David Greene and Dr. Anushka Drescher
UV System Low-pressure UV, Philips
Implementation Challenges for UV • Initial lack of sufficient water pressure • Fouling and scaling of UV lamps • O&M challenges from an initial lack of on-site training
Select Solutions to Implementation Challenges • The filtration pre-process was removed, or a slow-sand filter was installed, when necessary • The UV lamps, which were initially submersed, were positioned above the water flow

5.2. Background

This project was conceived during an outbreak of a mutant strain of cholera in India in 1993. Users were at significant risk of infection, collecting water from surface water sources or from hand pumps fitted on shallow tube wells. While the tragedy of this outbreak was significant, its rapid spread and deadly effect highlighted the poor capability of water treatment systems in rural India to eliminate biological contamination generally, and thus the precarious situation residents of these communities lived in with respect to epidemic outbreaks.

The goal was to disinfect communities' drinking water collected by hand from surface sources or from hand pumps fitted on shallow borewells. The water entering the device might have had a pressure of only a few centimeters of water column. The disinfection was required to be highly effective (exceeding USEPA guidelines) and affordable to local low-income community members, and the device needed to perform robustly in the difficult operating environment in remote areas of the developing world.

The primary objectives of the field test (Fig. 12) were to: 1) identify and correct any design problems and unanticipated technical flaws in the device, get feedback from an illustrative user community and from focus groups, and ensure the device's compatibility with the user preferences and requirements in South Asian communities; 2) evaluate and document the field performance of the device and its effectiveness in limiting the occurrence of waterborne biological contaminants in drinking water; 3) determine appropriate media and delivery systems for a) community placement and acceptance of the device, b) the necessary user education to assure sanitary and exclusive

Fig. 12 View of the Bhupalpur field test. The open well in the foreground is in disuse. The hand pump to the left of the well supplies water to the blue surge tank, which feeds into a large early-design UV Waterworks unit, partly seen within the low-height concrete walls. The villager noted that the flow of this first design (60 LPM) was far larger than any hand pump flow the villager had ever encountered. This led to the more compact revised design that disinfected a water flow of 15 LPM, better matched to the UNICEF India mark-II hand pumps widely installed in the developing world.

use of disinfected water for drinking and food preparation, and c) relevant community education in public hygiene and sanitary practices; and 4) determine the content and delivery systems for technical training of maintenance personnel, local management systems for community ownership and operation of the device to ensure its ongoing functioning.

The revised compact design ("UV Waterworks 2.0") was pilot tested in the Lily of the Valley children's hospice in the rural area adjacent to Durban in South Africa, as described in case study #15.

5.3. Technology description

The design team created an affordable and effective device that disinfects water using the equivalent of a 60 W light bulb at a cost of two cents per ton of water treated, treating 15 LPM, enough for 500 to 1500 people (Fig. 13). The unit delivers 120 mJ cm^{-2} to the water (three times higher than the 40 mJ cm^{-2} often recommended in the literature and regulations for drinking water disinfection, *i.e.*, ANSI/NSF-55 class A). It was designed to treat water with a UV extinction coefficient equal to that of the average effluent from United States municipal wastewater treatment plants. In laboratory testing with *E. coli* in dechlorinated tap water in Berkeley, UV Waterworks achieved a 6 log reduction in *E. coli* CFU (colony forming units). UV Waterworks was tested by third-party laboratories to ensure it could kill 15 different pathogenic bacteria (including *Campylobacter jejuni*, *Shigella*, *Salmonella typhi*, *Vibrio cholerae* and *Escherichia coli*) and multiple pathogenic viruses (including rotavirus and poliovirus), and also cysts of *Giardia*. Specific capabilities of the device include:

1. Can operate with unpressurized water.
2. Demonstrated inactivation of pathogenic bacteria and viruses in water with turbidity of up to 30 NTU.
3. Does not require a trained operator.
4. Requires maintenance every 6 months.
5. Fast-acting disinfection (hydraulic residence time = 12 seconds).

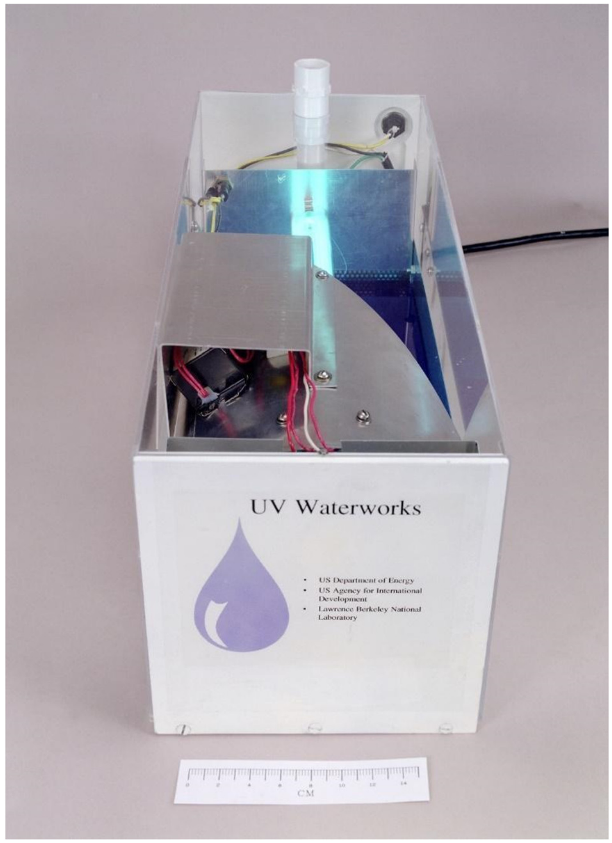

Fig. 13 UV waterworks, built with a glass cover for exhibits and displays to explain how the technology works.

5.4. Challenges and opportunities

To facilitate the robust installation of UV disinfection systems for users in rural India, a new UV system was conceived to address technical challenges. First, there was a lack of sufficient water pressure coming from hand pumps or surface water for the UV disinfection systems. The filtration pre-process generally was removed, and low-pressure cases where filtration was required were supplemented with a slow-sand filter. Secondly, the requirement (at the time) for a submersible-UV transparent sleeve around the bulb reduced the efficiency of the system as it rapidly became fouled with chemical and biological deposits. By suspending a bare UV bulb with an upper reflective surface above the flowing influent, a system was created with no solid surfaces between the UV source and the water, ensuring that the UV disinfection remained unaffected by chemical or biological fouling. Positioning the UV lamp above the water flow also improves lamp life, output, and UV fluence. Operating in the air keeps the temperature stable, improving performance and longevity while preventing fluctuations that reduce UV output.[40] Avoiding contact with water minimizes fouling, corrosion and moisture damage, reducing maintenance needs.[41]

The initial design was constructed of welded stainless steel, at a cost of $900 USD, consumed 40 W and reduced the bacterial colony forming units (CFU) per 100 mL at 30 LPM from 100 000 to less than one, *i.e.*, disinfection that meets WHO and EPA standards.

After a second workshop in India in May 1994, the design was field tested at several sites in India, including at Bhupalpur, from 1994 to 1995. A hand pump was used to supply contaminated well water to the UV Waterworks unit, which was powered by a 12 V car battery. The Indian communities reported that the flow capacity of the device (60 LPM) was far higher than necessary, and the devices were bulky and costly. In response, a revised prototype was developed that still used 40 W but disinfected 15 LPM. This new design was better matched to the flow rate of the widely used UNICEF India Mark-II hand pump, was more compact and had a substantially lower manufacturing cost. This design, completed in December 1995, exhausted all project funding. The design has seen only minor modifications since then, as the project effort has shifted to testing, troubleshooting and promotion.

5.5. Lessons learned

The small-scale, energy-efficient and low-maintenance design of UV Waterworks has created a uniquely affordable and effective device: disinfecting water using the equivalent of a 60 W light bulb at a cost of two cents ($US) per ton of water treated, treating 15 LPM, enough for 500 to 1500 people. As a result, UV Waterworks offers a practical means of providing many communities in developing nations with readily accessible, disinfected drinking water.

The Indian communities informed us that the flow capacity of the device was much higher than necessary, and the devices were too bulky and costly. In response, a revised version was delivered with lower flow rates and lower costs. Socially, the lack of trained personnel on-site and the difficulty in traveling the large distances required in rural India presented a skill deficiency challenge.

5.6. Acknowledgements

This project was made possible thanks to seed funding and support from the Energy Efficiency Program of USAID that spanned from 1995 to 1998.

6. LP UV treatment of wastewater at a hydropower facility in Lao PDR

6.1. General data

Type of Project Wastewater treatment
Location Staff Operator Village of the Theun Hinboun Hydro Power Company (THPC), Nahin village, Khounkham District, Khammouane Province, Lao PDR
Project Period 2011 to Present
Scale 70 m^3/day, serving approximately 70 households (up to a max of 700 users).
Affiliation & Contact Bremen Overseas Research and Development Association (BORDA) The University of British Columbia Dr. Sara E. Beck, sara.beck@ubc.ca
UV System Low-pressure UV, four Sanitron S50C lamps in parallel
Implementation Challenges for UV • Influent water quality too turbid with high TSS concentrations • Flow rate too high • Fouling and scaling of UV lamps • Insufficient O&M
Select Solutions to Implementation Challenges • Improved pretreatment and maintenance of wetlands • Additional lamps used to increase disinfection capacity • Regular sleeve cleaning protocols and O&M

6.2. Background

In many Southeast Asian countries, including Lao People's Democratic Republic (PDR), wastewater flows directly into receiving waters. To address this problem, in the 1990s, low-cost and low-technology decentralized wastewater treatment systems gained recognition and were promoted as appropriate and sustainable solutions for low- and middle-income areas. In Southeast Asia, the Bremen Overseas Research and Development Association (BORDA), a German non-governmental organization (NGO), promoted these Decentralized Wastewater Treatment Solutions (DEWATS).[42]

In 2011, BORDA installed a UV disinfection system for decentralized wastewater treatment at the site of an existing wastewater treatment plant at the Staff Operator Village of the Theun-Hinboun hydropower generation plant. The original wastewater treatment system, which was in use from 1995 to 2009 and used a mechanical-activated sludge system, had stopped functioning due to high costs and a lack of O&M knowledge and capabilities. As a result, the system had high odors and was no longer meeting effluent wastewater quality discharge standards. The company requested support from BORDA to upgrade the plant in 2010. The upgraded plant, which became operational in October of 2011, included a pretreatment system (Fig. 14) with a grease trap, settler, anaerobic baffled reactor, anaerobic filter, planted gravel filter, and aerobic polishing pond prior to UV disinfection, before discharge into a natural stream. At the start of operation, the wastewater plant was serving over 70 households and a maximum of 700 users with a treatment capacity of 70 m^3 per day.

6.3. Technology description

The UV system consisted of four Sanitron ultraviolet water purifiers (Model S50C, 75 LPM) manufactured by

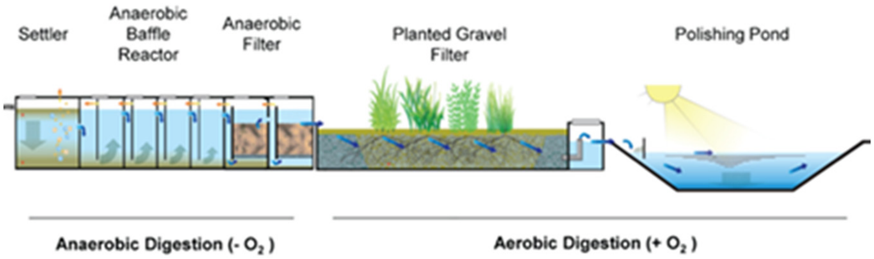

Fig. 14 Pretreatment of wastewater prior to UV disinfection.

Atlantic Ultraviolet Corporation, which used STER-L-RAY low-pressure germicidal lamps, emitting at 254 nm, encased in a stainless-steel chamber. The lamps are horizontal, operated in parallel, in two groups of two (Fig. 15). This particular system also included a Guardian digital UV light monitor, which was installed in the visualization port to detect decreases in UV irradiance from, for example, a) fouling of the quartz sleeves; b) poor water quality, which would block the UV transmission through the water; or c) depreciation of the lamp output.

6.4. Challenges and lessons learned

THPC called on BORDA to troubleshoot the wastewater treatment system and a site visit was organized in March of 2016, approximately five years after installation.

6.4.1. Influent water quality. Perhaps the biggest challenge to the UV system was the quality of water in the influent. The water did not meet the standards for which UV disinfection is effective. In general, UV disinfection is not effective for water with a TSS concentration higher than 30 mg L^{-1}.[43] Additionally, the Sanitron Ultraviolet Water Purifier brochure recommended a maximum TSS of 10 mg L^{-1} and a max turbidity of 5.0 NTU for the system to effectively treat the water; however, the turbidity measured in the UV influent was between 10 and 50 NTU and TSS concentrations from the aerobic pond were up to 23 mg L^{-1} to 49 mg L^{-1}. There were no specific UV absorbance values at 254 nm (UVA_{254}) set for the system and the THPC plan did not have a spectrophotometer to measure the UV absorbance or transmissivity. Instead, the guidelines set by the manufacturer specified TSS, turbidity, flow rate, iron (<0.3 mg L^{-1}), manganese (0.05 mg L^{-1}) and hardness (<6.0 gpg, which is considered moderately hard) to ensure adequate disinfection.

One suggestion for improving pretreatment of the water prior to UV disinfection was to install a tube settler in the aerobic pond so that particles would attach to it and settle down. Sand filters and membrane filters also would reduce the influent turbidity; however, they would require routine maintenance. Another suggestion from colleagues at the Asian Institute of Technology was to better maintain the wetlands in the planted gravel filter by harvesting, for example. Since it had been operating for four and a half years, solids would have accumulated on the media, which increases the contaminants flowing through. Maintenance would require cutting the plants, removing sludge that had accumulated on the top surface, and washing or replacing the media.

6.4.2. Flow rate. During a site visit in 2016, it was discovered that the system was being operated at a higher flow rate than that recommended by the UV manufacturer. For the wastewater to receive adequate exposure to UV light, the system needed to stay within the design flow rate. During the site visit, the team had been investigating why the flow rate was so high given that the number of users was at half the maximum capacity. It was suggested that the flow rate be decreased to increase the exposure time.

Another suggestion to increase UV exposure was to route the four lamps in series instead of in parallel; however, the flow rate with the lamps operating in parallel already was exceeding that recommended by the manufacturer. Therefore, routing them in series would not have been sufficient for meeting the treatment demand. Adding more lamps would have been one solution to increase the disinfection capacity while maintaining or lowering the flow rate.

Fig. 15 UV disinfection system.

6.4.3. Fouling and scaling of the UV lamps. Although the lamps incorporated a mechanical wiper assembly for periodic cleaning of the quartz sleeve, the wiper may not have been routinely used or perhaps the lamps were fouling or scaling regardless of the wiping. Some of the lamps exhibited deposits, and it is believed that scaling on the lamps was occurring due to high calcium concentrations in the area.

The low-pressure UV lamps used were designed to last for 10 000 hours, or 14 months of continuous operation. BORDA recommended that they be replaced every year to be conservative. The THPC operators confirmed that the lamps were only six months old; therefore, their output was not the source of the problem. It was recommended that the operators use a solution to clean the lamp sleeves including citric acid, phosphoric acid or Lime Away to dissolve calcium and magnesium deposits or another solution recommended by the UV reactor manufacturer that is consistent with the NSF/ANSI (the Public Health and Safety Organization/American National Standards Institute) Standard 60 on Drinking Water Treatment Chemicals – Health Effects. Pilot studies lasting five to 12 months using UV reactors with low-pressure and medium-pressure lamps found that standard cleaning protocols and wiper frequencies (one to 12 cleaning cycles per hour) have been sufficient to overcome the effect of sleeve fouling with water that had total and calcium hardness levels less than 140 milligrams per liter (mg L^{-1}) and iron less than 0.1 mg L^{-1}.[44,45]

6.4.4. Insufficient operation and maintenance. The THPC had assigned three staff members to operate and maintain the decentralized wastewater system, and the team was trained to monitor the UV irradiance and replace the UV lamps; however, some of the steps may have been overlooked four and a half years later as regular maintenance was not occurring. Although the lamps had been replaced, the low irradiance values suggested that they were not being regularly cleaned.

7. Rainwater treatment by biosand/biochar and UV LEDs in rural Kenya

7.1. General data

Type of Project	Rainwater collection and treatment by Biosand/Biochar and UV LED system for household use
Location	Nyamesocho rural village, Bomachoge Borabu constituency, Kisii County, Kenya
Project Period	September 2022 to July 2023
Scale	Household, 7.5 LPM
Affiliation & Contact	The University of British Columbia Dr. Paul Onkundi Nyangaresi, paul.nyangaresi@ubc.ca Dr. Sara E. Beck, sara.beck@ubc.ca
UV System	UV LED, 265 nm, Klaran WS Series Retrofit Kit, Crystal IS
Implementation Challenges for UV	• Power cut-offs • Accessibility of UV LEDs • Affordability
Select Solutions to Implementation Challenges	• Household preferred UV compared to chlorine because of taste • Solar panel was able to supply consistent electricity

7.2. Background

Although water is available in the community in the rural village of Nyamesocho, Kisii County, Kenya, residents must walk long distances (>1 km) through steep terrain to fetch water from humanmade springs and shallow surface streams. During the rainy season, water from the springs and surface streams is often colored and with high turbidity; in fact, it is highly contaminated. Also, people find it difficult to access the water sources due to inaccessibility and slipperiness of the paths used while walking to them. Therefore, most of the household families (between 10 to 20 people) find it appropriate to collect rainwater in storage water tanks, which then is used for their daily household activities, such as cooking and drinking.

The collected rainwater is commonly stored in polystyrene tanks, metal jerry cans, clay pots and other water storage containers. Galvanized corrugated iron sheets are the commonly-used housing roofing material for most communities in Kenya, including the rural communities at Nyamesocho village (Fig. 16). Therefore, the rainwater is often collected from such roofs. Notably, if not filtered, the collected and stored rainwater is contaminated by dirt found in the rooftops originating from bird and some animal droppings, tree leaves, *etc.* In the past, visible worms frequently have been seen in the stored rainwater (Fig. 16), which is a confirmation of the reports on the growth of microbial contaminants within water storage containers.[46,47] Also, if the water is stored for long periods of time, it can produce an unpleasant smell, which can prevent people from drinking it. Therefore, this project was designed to collect,

Fig. 16 Worms in water collected from water storage tank.

filter and disinfect rainwater by ultraviolet light-emitting diodes (UV LED) for use at household point of use. Future work in the area will involve designing and building similar but larger water treatment systems to serve more people in the community, including systems in community schools within the rural villages as well as within more densely populated poverty-stricken areas within Nairobi.

7.3. Technology description

The rainwater treatment consisted of biosand/biochar and flow-through UV LED water filtration/disinfection systems (Fig. 17a). The biosand/biochar system (Fig. 17b) helped in removing suspended particles collected from the roof that can hinder UV light penetration into the water. The top of the 5000 L rainwater collection tank was covered with a mosquito net to filter large debris and particles that may enter the tank. Then, the rainwater, controlled by an automatic water level control valve, passed through different layers of gravel, sand and charcoal placed inside a 100 L polystyrene tank before being collected in another clean 100 L polystyrene tank, followed by a UV LED disinfection unit (265 nm Klaran WS Series Retrofit Kit). The UV LED disinfection system contained UV LEDs emitting at 265 nm and had a maximum flow rate of 2.8 LPM. Back-calculating the fluence delivered by the reactor using an MS2 log inactivation standard curve, yielded an applied fluence of over 7.5 mJ cm^{-2} at an average flow rate of 1.8 LPM; however, this value was for a UV transmittance of 94%, which was conservative for the ~98% UVT rainwater.

For continuous operation of the UV LED system, it was powered by automatic interchangeable electricity from both solar panels and grid lines. Although the cost of the treatment system seemed expensive, the installation and operation were relatively easy.

7.4. Challenges and opportunities

7.4.1. Availability and cost. In general, UV LED water disinfection systems are inaccessible and expensive not only in Kenya, but also in Africa. The system used in this work was purchased from the United States and currently costs approximately 200 USD, which is not affordable to most people in the local community, especially within a household, who earn less than 1 USD per day. When discussing the system with the members of the household where it was installed, they were astonished with the price; hence, they viewed it as cost prohibitive. Therefore, most of them commented that they will opt to continue using the original water, which has not been treated with UV, unless the cost of the UV system decreases substantially. However, when given options to choose between chlorinated and UV-treated water, they were in favor of the UV-treated water since both the taste and smell of the chlorinated water is undesirable for them.

7.4.2. Flow rate. Using this particular UV LED reactor, with a maximum flow rate of 2.8 LPM, the flow rate was not quite high enough for daily operation. Therefore, the UV LED system was removed after approximately 11 months of operation with the biosand and biochar system still in operation and working effectively for the household.

7.4.3. Electrical power. Although most of the local communities in the rural village at Nyamesocho are connected to grid line electricity, the electricity is not continuous, which affects the functioning of the UV LED

Fig. 17 (Left) Rainwater collection, filtration and disinfection system. (Right) Biosand and biochar layers within the filtration system.

disinfection system. However, for the household where the system was tested, we connected the UV LED reactor with a 50 W solar panel, consisting of a 33 Ah solar battery, a 150 V solar power inverter and 10 Ah solar charge controller, ensuring continuous power for both the UV LED disinfection system and also for lighting.

7.5. Lessons learned

A UV LED system can be appropriate for water disinfection in rural marginalized communities. However, the system used is not yet easily accessible, and it is highly expensive for the local communities.

8. Implementation of low-cost UV disinfection systems to provide safe drinking water at primary schools in rural Kenya

8.1. General data

Type of Project
Potable water treatment
Location
Eldoret, Kenya
Project Period
2017 to 2020
Scale
System of primary schools consisting of 400 students and staff members 7.5 LPM
Affiliation & Contact
Division of Environmental and Ecological Engineering and Lyles School of Civil Engineering, Purdue University Margaret Busse, busse@purdue.edu Dr. Ernest R. Blatchley III, blatch@purdue.edu
UV System
Low-pressure UV, VIQUA VT1
Implementation Challenges for UV
• Energy surges led to frequent burnout of lamps and require replacements • Unavailability of locally-sourced UV systems and parts • Operators did not feel comfortable conducting water quality testing on their own
Select Solutions to Implementation Challenges • Consider the power quality supplying the UV • Use a local UV equipment supplier

8.2. Background

This study was designed to install water systems at three locations – two with UV disinfection systems and one with a system utilizing chlorine for disinfection – in order to understand whether improving the effluent taste of water from treatment systems can help overcome issues with adoption. The school initially set to receive the chlorination system was informed about the UV option by another school and requested to have the UV system or no treatment at all as the school did not want the chlorine to impact the taste of its water. Therefore, a fourth school was selected to receive chlorine, and three total UV systems were installed. Schools were selected for inclusion in this study because of the need to provide water to students who depend on a consistent supply of safe water outside of the home. Schools are also a location that consistently are occupied and managed by the same group of people, which, it was hoped, would allow for consistency in system operation. Furthermore, children can be agents of change for improved health communication in the home.[48,49] The specific schools were selected as study sites based on the need for the schools to 1) be within walking distance of each other to allow for centralized system O&M, 2) have no current water treatment method for the water they consume, and 3) have water currently piped to the school (as we were just studying water treatment methods, and the scope of study did not include obtaining water for the schools). Finally, the water treatment systems were designed to minimize the amount of user interaction required for system operation without compromising treatment quality. The water source selected was a nearby spring that was mixed with rainwater when available. The systems consist of a slow-sand filter followed by a storage tank. Then when a tap is turned on, the water moves from the storage tank to the tap, passing through a UV treatment system.

8.3. Technology description

The UV reactors for these systems were powered by a 30 W solar panel wired to a charge controller (10 A), with output to both a standard car battery (30 A h) for energy storage and directly to the UV reactor for power. The UV reactors used were low-pressure (LP UV) lamp reactors designed to operate at 7.5 LPM at 95% UV transmittance at 254 nm (UVT_{254}). At this flow rate, they provide a UVT_{254} dose that exceeds 16 mJ cm^{-2}. These systems utilized a 9 W lamp with a 9000 hour useful lamp life and required 12 VDC for operation. Each system also had a switch for turning the system off when the system would not be in use (*e.g.*, at night, during school breaks) to extend the lamp life.

Local plumbers and electricians were hired to install the systems, and a welder built solar panel roof brackets and boxes to contain the systems and prevent tampering (Fig. 18). The boxes to prevent tampering, which were requested by the schools, were designed with a window to allow the operator to easily check whether the system was on or off. The systems were designed to cost around $250 USD, including all components and installation costs. This system was installed directly before the drinking water taps for immediate consumption or use after treatment (the water was not stored post-UV treatment). Therefore, it was only available on demand, because the stored water could become contaminated post-treatment with no residual disinfectant in the water.[50]

8.4. Challenges and opportunities

When the school communities were presented with the treatment technology options, UV seemed to be preferred. It is important to note that this information was gathered through candid, informal conversations. Further, one of the school directors was a vocal advocate for the project and the technology after the importance of water treatment in general and the process of UV treatment were described.

Fig. 18 System components that were designed and constructed by the welder; (left) a solar panel bracket holds the panel in place on the roof and locks so the panel cannot be stolen, and (right) a box to protect the system from tampering.

All of the UV system components were functional in 2020, but they were not being used consistently due to technical constraints. One major barrier was a problem with energy surges that were not properly mitigated by the charge controller in the system. There were issues with both locally and United States-sourced low-cost charge controllers. As a result, lamps would frequently burn out and need to be replaced. A surge protector was installed (which was unavailable locally), but the surges were frequent, requiring that an operator check the system before each use, which was not practical. Further, parts for the VIQUA VT1 system were not available locally and needed to be sourced from a company in Uganda (which needed to order them from Canada). Alternate UV systems were available at the local water equipment supplier, Davis and Shirtliff. Rigorous testing of locally available supplies and design of treatment systems using only these supplies would have prevented many of the technical issues encountered.

Challenges with system testing and maintenance were also encountered. Testing was set up to be conducted by the school maintenance worker and a science teacher. They would then use WhatsApp to send pictures of the results weekly. Unfortunately, they did not feel comfortable conducting Aquagenx compartment bag tests, which is a field test to detect *E. coli* in water samples. Further, the UV transmittance readings we received proved unreliable due, it is believed, to the continual need for calibration of the low-cost UVT instrument. Thus, many of the important tests needed to maintain system compliance were difficult to obtain.

8.5. Lessons learned

Based on the schools' excitement around the ability to treat their water without impacting its taste, there is considerable potential for the adoption of low-cost UV systems if technical barriers can be overcome. Careful consideration should be given to the barriers and impacts beyond just those directly linked to the UV systems, such as ethical constraints, government influence and social barriers.

9. Household UV disinfection for drinking water in rural Mexico

9.1. General data

Type of Project Drinking water
Location Baja California Sur, Mexico, State of Chiapas, Mexico
Project Period 2006 to 2014, 2018 to 2022
Scale Approximately 600 rural households, 5 LPM system
Affiliation & Contact Cantaro Azul Ane Galdos, ane@cantaroazul.org Dr. Fermin Reygadas, fermin@cantaroazul.org
UV System Low-pressure UV, positioned above water
Implementation Challenges for UV • User adoption: preventing users from sporadically drinking untreated water. • Scaling up requires efforts to reduce production costs, increase product lifetime and integrate such treatment methods into government programs to subsidize water treatment solutions.
Select Solutions to Implementation Challenges • Human-centered perspective • Service delivery approach • Water was treated at the point of entry into home to reduce contamination • UV was beneficial because it did not impact water taste

9.2. Background

In Mexico, 25 million people live in rural communities. Rural communities with high-enough population density can have piped water systems, but a 2014 study by a local NGO, Cantaro Azul, reported that less than 20% of the piped water was disinfected. For less-densely populated areas, water is often obtained at the household level through means such as rainwater harvesting or truck deliveries. The Health Ministry has widely promoted boiling and point-of-use chlorination (using bleach) for drinking water, but Cantaro Azul reports less than 5% of the rural population practices these methods on a consistent basis. Boiling is challenging due to the need to collect wood and the long waiting time, and chlorination is unpopular due to the objectionable taste. UV disinfection is an attractive alternative because it relies on electricity, which is widely available throughout Mexico, either from community grids or solar panels.

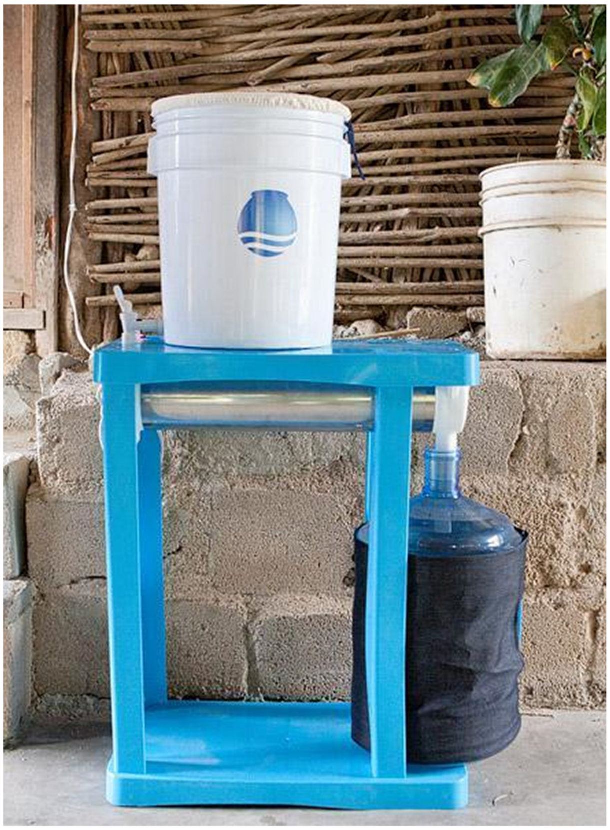

Fig. 19 Mesita Azul household water treatment system with an open-channel UV reactor (silver cylinder) fed by gravity.

9.3. Technology description

From 2006 to 2014, Cantaro Azul partnered with the University of California (Berkeley) to install UV drinking water disinfection systems for 400 rural households in Baja California Sur, Mexico. The UV system, called Mesita Azul, was a 5 LPM low-pressure UV reactor delivering an estimated dose of 120 mJ cm^{-2} through a 15 W mercury lamp. The lamp was positioned above the water to avoid scaling (Fig. 19).

A second iteration of UV installations was undertaken from 2018 to 2022 through Cantaro Azul's SAFEWATER program. Here, 187 treatment units were installed in rural households in the state of Chiapas, Mexico. The SAFEWATER system consists of a point-of-entry water treatment unit that includes a 250 L raw water container located in the bottom level of the support structure and a 250 L container for treated water at the top level (Fig. 20). The bottom container can receive water from multiple sources, including piped water (*e.g.*, a nearby spring or well), a hose from a storage tank (*e.g.*, rainwater harvesting) or poured in directly when manually collected. Water is pumped from this container, through the treatment components and into the top container for safe storage. The treatment process consists of two pleated filters with nominal pore sizes of 5 μm and 1 μm, an activated carbon filter and a UV disinfection chamber (either the same open-channel system as the Mesita Azul or a common pressurized system). The key element of the SAFEWATER system is that it uses gravity to distribute water from the top container through 1/2″ PVC pipes to two to five taps installed within the home.

9.4. Challenges and opportunities

The initial 2006 to 2014 study of 400 rural households reported an 80% uptake rate of the offered UV systems. During the study, the households with the UV treatment experienced a reduction in the number of positive *E. coli* results in drinking water from 60% to 20%. It was observed, however, that since the UV system was designed only to treat the drinking water and not water intended for non-potable uses (handwashing, laundry, *etc.*), an estimated 50% of the people in the study continued to sporadically drink untreated water. It was concluded that the presence of non-

Fig. 20 The 250 L SAFEWATER system (left) with the encased LP UV lamp and activated carbon filters (right).

disinfected water in the household compromised the potential for maximum benefit from the treated drinking water.

The second phase of the study (the SAFEWATER project from 2018 to 2022) was designed to deliver treated water for all uses in the household to minimize the risk from access to untreated stored water. During the study of 187 installations, the rate of positive *E. coli* incidences was reduced from 80% in the untreated control group to 20% in the treated systems. It was observed that only 16% of the households showed evidence of people sporadically drinking from non-treated stored water.

9.5. Lessons learned

This study demonstrated that UV disinfection can offer important advantages over chemical treatment, including not impacting the taste or temperature of water and being able to rapidly treat large quantities of water that can meet all household water needs and reduce the risk of people drinking untreated water.

Cantaro Azul reported that scaling UV disinfection in rural communities requires efforts to reduce production costs, increase the lifetime of the products and integrate such treatment methods into government programs that partially or fully subsidize water treatment solutions in marginalized communities. To achieve this goal, it is important to form alliances that support all dimensions of the implementation of UV, from research and innovation to product design, capacity building, supply chain development, community mobilization and public policy advocacy.

10. Filtration, reverse osmosis and UV for community water treatment in Nicaragua

10.1. General data

Type of Project Potable water treatment
Location Rama Cay, Nicaragua
Project Period 2018 to 2022, Project Not Constructed
Scale Community-scale, 5.2 LPM
Affiliation & Contact Messiah University Daniel Ma, ma.1081@buckeyemail.osu.edu Prof. Michelle Lockwood, mlockwood@messiah.edu
UV System Low-pressure UV, VIQUA VT4
Implementation Challenges for UV • Power source only operates eight hours per day • Community buy-in on potable water treatment • Political tension
Select Solutions to Implementation Challenges • Emphasize community buy-in and communication • Maintain relationships with local communities and NGOs

10.2. Background

Rama Cay is an island located near Bluefields, Nicaragua. The population is approximately 200 families, totaling 1400 people. Friends in Action International (FIA) is a faith-based, non-governmental organization that has worked in the Rama community for over 15 years. Individual families from Rama Cay previously obtained drinking water by traveling 30 minutes by boat to purchase bottled water at the mainland. In 2018, FIA invited Messiah University student teams to design a water system solution for the community.

10.3. Technology description

Each system was designed to provide 1500 L of drinking water per day, requiring five hours of generator operation per day. A submersible well pump is controlled by a 30 psi to 60 psi pressure switch and delivers water to the treatment system. To protect the well and the pump, the well pressure switch must be turned on manually if the pressure drops below 20 psi. The multi-barrier treatment train includes prefiltration (three-stage filters: 100 μm, 10 μm and 5 μm), reverse osmosis (RO) to remove salts and bacteria, UV disinfection as an additional barrier for microbial treatment and calcite contactors to balance water chemistry (Fig. 21). For point-of-use UV disinfection, a VIQUA VT4 Model was selected. At the operating flow rate of 5.2 LPM, the UV system is expected to deliver >40 mJ cm^{-2} (for UVT > 75%).

A pressure tank maintains water pressure (15 psi) for the RO unit and is controlled by a 15 psi pressure switch. Electrical controls are in place to detect when the storage tank is full, and a float switch shuts off the RO unit with a solenoid valve. CPVC piping was selected for the UV system inlet and outlet to prevent pipes from melting during periods of no flow in the UV reactor. No chlorine residual was provided in this system design. The ambient temperature in Rama Cay is between 72 °F and 93 °F throughout the year, so bacteria could propagate in the storage tank. The design assumes the community uses nearly all the water in the tank to prevent excessive water from stagnating overnight. The entire system (RO and UV) shuts down when the generator is shut off each night.

The capital cost of each individual water system was approximately $9400 USD, including RO ($4500 USD), UV disinfection ($325 USD), calcite contactors ($375 USD), tanks and plumbing ($3000 USD) and electrical components ($1150 USD). For each system, the replacement costs are $345 USD every two years for RO pre-filters and membranes, $84 USD per year for UV lamps and $90 USD per year for calcite filter media. This is planned to be funded by the Friends in Action Organization. The final system will be housed in a concrete building and community members will be able to collect potable water from tanks.

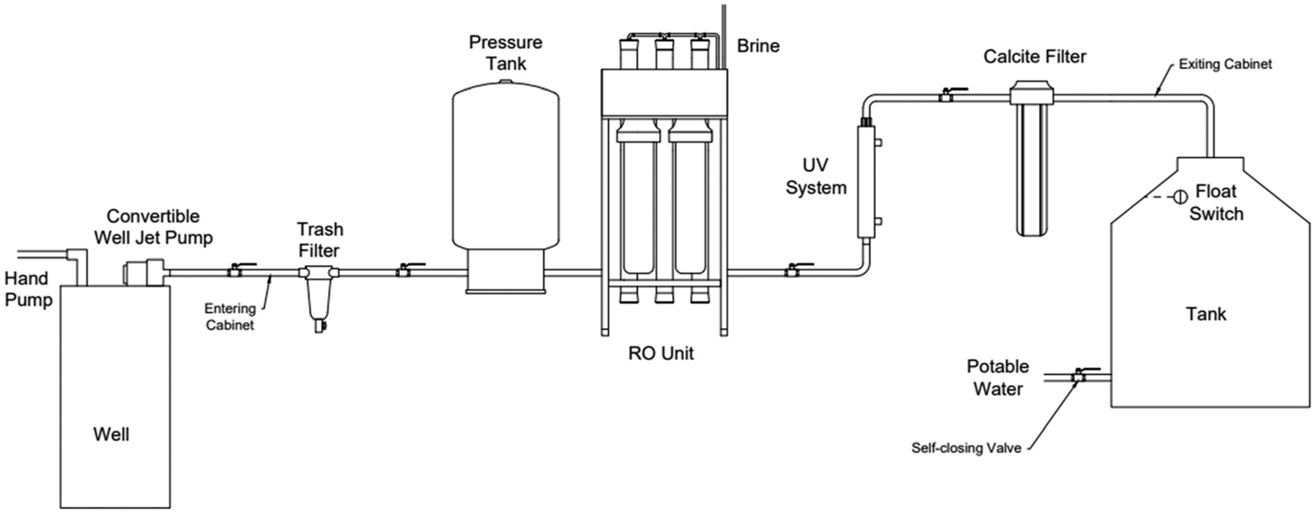

Fig. 21 The multi-barrier treatment train includes prefiltration, reverse osmosis (RO), UV disinfection and calcite filters.

10.4. Challenges and opportunities

In July 2019, students performed water testing and well recharge tests (the wells recharge from a nearby saltwater bay) to determine the quality and quantity of water in two wells, each located on the northern and southern side of the island. *E. coli* was detected (4.7 to 48 MPN per 100 mL) in untreated samples from the wells using Aquagenx Compartment Bag Tests. Total dissolved solids (277 to 520 mg L^{-1}), total hardness (85 to 154 mg L^{-1}), alkalinity (20 to 60 mg L^{-1}) and conductivity (360 to 459 μS cm^{-1}) also were measured. Generator-driven electricity is available for eight hours a day in limited locations. Politically, the island functions as two communities, one northern and southern community. Therefore, two water systems were required. Environmental concerns included determining appropriate location for RO brine disposal to avoid disrupting marine life (*e.g.*, shrimp farms and fishing). Not all parts could be sourced in Nicaragua. Therefore, in Spring 2022 parts were purchased in the United States and placed under the care of FIA for final shipment to Nicaragua. This course of action would have been less desirable than local sourcing of equipment if not for the long-term relationship and ongoing partnership FIA has on Rama Cay.

10.5. Lessons learned

As of June 2022, the project was completely designed, but implementation was delayed indefinitely due to political tensions on the island. The students learned the importance of patience in cross-cultural project work. Other student teams should place emphasis on written documentation and oral communication to ensure smooth transfer of knowledge between multiple student groups over the course of multiple academic years. To ensure longevity of projects, it is critical to focus on obtaining local community buy-in rather than the work being done. This project demonstrates the necessity of community buy-in despite three years of communication with our community partner, FIA. For success in development projects, it is imperative to continually rely on NGO relationships with local communities, to demonstrate compassion through heart-felt listening and to adopt a constant posture of learning.

10.6. Acknowledgements

The authors thank Ray Knepper, Project Team Technical Advisor; Tim Johnston, Friends in Action International; Messiah University and The Collaboratory for Strategic Partnerships and Applied Research; Village Water Ozonation Systems and all project members from 2018 to 2022.

11. Solar-powered UV LED system for drinking water disinfection in the Philippines

11.1. General data

Type of Project Potable water treatment
Location Panobolon Island, Guimaras, Municipality of Nueva Valencia, Western Visayas, Philippines
Project Period September 2018 to Present
Scale 2 LPM, 150 L/day
Affiliation & Contact University of Tokyo, University of San Agustin and Philippine Science High School Western Visayas Campus Dr. Kumiko Oguma, oguma@env.t.u-tokyo.ac.jp
UV System UV LED, 280 nm, Nikkiso
Implementation Challenges for UV • Potential photoreactivation of microorganisms • Seasonal variation in water quality • Insufficient microbial inactivation
Select Solutions to Implementation Challenges • Solar power as a suitable, alternative power source • Increase contact time and number of LEDs • Reduce exposure to sun to limit photoreactivation • Disinfection of storage tank

11.2. Background

Ensuring universal and equitable access to safe drinking water can be especially challenging in off-grid islands with limited access to both electricity and clean drinking water. In Western Visayas, on Panobolon Island, groundwater harvested from dug wells used for drinking often was at risk of microbial contamination. During pilot sampling in September 2018, all nine deep wells tested were positive with *E. coli*: concentrations reached as high as 5000 CFU per 100 mL. Moreover, DNA sequencing of bacterial isolates from a well suggested the presence of *Shigella flexneri*, a pathogen which can cause foodborne and waterborne diseases.[51]

A team from the University of Tokyo worked with the University of San Agustin and the Philippine Science High School Western Visayas Campus to install a solar-powered UV LED system (Yu Jeco, Larroder and Oguma, 2019). Since the island has no access to the commercial power grid, the solar-powered UV LED disinfection system was introduced by the team as a feasible technology (Fig. 22). The team set a long-term goal to let the residents learn how to operate and maintain the system by themselves; therefore, community members were encouraged to join a free workshop to learn the basics of public health and UV disinfection.

Fig. 22 Pilot setup of solar-powered UV LED water disinfection system in Panobolon Island, Guimaras, Philippines. The UV LED module is enclosed in the yellow circle.

11.3. Technology description

The pilot flow-through UV LED module contained a single 40 mW 280 nm LED (Nikkiso, Japan). The handheld module originally was designed for point-of-use applications to disinfect flowing water at the tap at 2 LPM; therefore, the same flow rate was adopted to treat an estimated 150 L per day of water for a community of 50 people (assuming 3 L per capita per day for drinking water only). During lab testing, the UV LED system achieved between 2.5–3 log-inactivation of *E. coli* (K-12 IFO3301) at a flow rate of 2 LPM. The test matrix in PBS had an initial concentration of *E. coli* of 10^6 CFU mL^{-1} and a UVT at 280 nm of 96%.

Water quality conditions in the field were as follows (mean ± SD): turbidity = <0.1 degree (Japanese turbidity unit), color = 0.8 ± 0.1 degree (Japanese color unit), hardness = 46.4 ±1.3 mg L^{-1}, iron = <0.02 mg L^{-1}, manganese = <0.005 mg L^{-1}, temperature = 17.1 ± 1 °C, pH = 7.7 ± 0.02, conductivity = 11.0 ± 0.25 mS m^{-1}. Concentrations of microorganisms in the raw water were as follows: *E. coli* up to 1.5 CFU mL^{-1}, total coliform up to 2.5 CFU mL^{-1}, standard plate count up to 16 CFU mL^{-1}, and heterotrophic plate count up to 2500 CFU mL^{-1}. *E. coli* and total coliform were not detected in the UV LED effluent for the duration of the pilot testing (n = 21 samples, 12 months), except for one detection of *E. coli* after UV disinfection. The average log-inactivation of heterotrophic plate count was 0.77 and 1.83 for 2 LPM and 10 LPM operation, respectively.

The UV LED was rated to operate at 12 V and 350 mA, which was powered by a 150 W commercial silicon solar panel generating approximately 325 Wh per day with a battery storage of 50 Ah (Fig. 23). The region has an estimated annual mean of 4.3 kWh m^{-2} per day, as detected at Iloilo City. The system was only operated during the period of piloting.

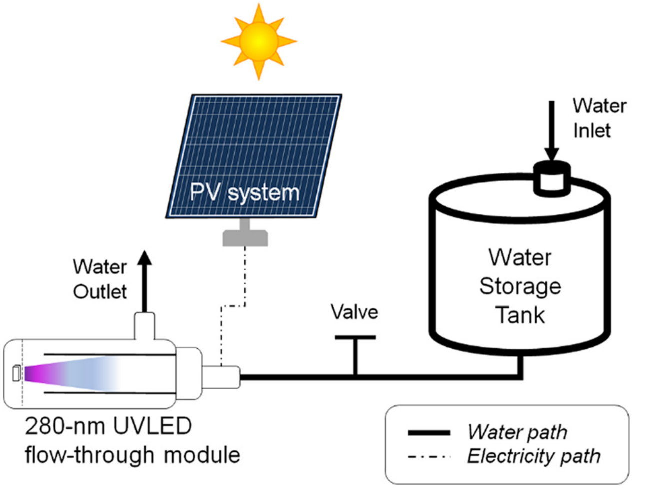

Fig. 23 Simplified schematic of the solar-powered UV LED water treatment system.

11.4. Challenges and opportunities

Based on the challenges encountered during the pilot tests, the following recommendations are proposed for the final implementation of the solar-powered UV LED water disinfection system:

1. The UV LED flow-through module adapted in the initial trial was not enough for inactivation performance, as treated water was still occasionally positive with *E. coli*. Modifying the current prototype module, or using different modules with higher inactivation performance, would be necessary. Alternatively, UV LED exposure during storage, instead of flow-through treatment, would be an option.

2. Photoreactivation of microorganisms under strong sunlight could be an issue in the field, as this was slightly observed during this field testing. Sunlight protection measures should be taken. For example, light-screening containers are recommended to bring the treated water back home.

3. Seasonal variations of both groundwater quality and solar radiation should be considered in the treatment design process as these can affect system performance. These factors also should be monitored over a long period of time.

11.5. Lessons learned

Results revealed that regulated solar power is a suitable alternative power source for a UV LED apparatus and that the proposed system is socially accepted by the residents. Therefore, it can be concluded that, once the system is modified to provide higher fluence to achieve better inactivation performance, the solar-powered UV LED water disinfection system could be a viable solution to improve the microbial safety of the drinking water.

12. A solar-powered water treatment system for rural areas of Rwanda

12.1. General data

Type of Project
Solar-powered water treatment system for rural areas
Location
Rwanda
Project Period
2010 to present
Scale
Water treatment in schools and hospitals in rural areas 5 LPM
Affiliation & Contact
Nedap N.V., Groenlo, Netherlands Tonnie Telgenhof, tonnie.telgenhof@nedap.com
UV System
Low-pressure UV, 20 W, Solar-powered
Implementation Challenges for UV
• Financing units and maintenance • Local attendance for installation, maintenance, service and education
Select Solutions to Implementation Challenges
• UV was preferred due to its lower cost and lesser maintenance requirements

12.2. Background

In the 2010s, the Impala Foundation identified several schools and hospitals across Rwanda where there was (1) a lack of safe drinking water and/or (2) a lack of a reliable grid electricity to power a decentralized water system. Some of these sites had intermittent piped water. The available water sources at the rest of the sites included untreated rainwater, or untreated water from rivers or dug wells that would need to be piped to the point of use. Several of the schools also reported high incidences of children not attending school due to sickness. Some schools were using point-of-use chlorine disinfection but reported that it was expensive and/or difficult to control. Solar power or 12 V batteries were typically the best available energy sources to support a new water system. In response to these challenges, Nedap (a UV technology manufacturer), the Dutch Soroptimists (an NGO), and the Impala Foundation (also an NGO) collaborated to provide a UV-based drinking water treatment solution (Naïade) that allowed the efficient usage of present water sources, included a multi-barrier treatment process, required limited storage of water and, most importantly, was low cost. In addition, there also were requirements for easy transportation, technical education at the user's level and maintenance of the system. This report describes the usage of Naïade systems in schools and hospitals in Rwanda.

12.3. Technology description

The Naïade is a stand-alone, solar-powered water purification unit which can be set up and ready for use within 30 minutes. No special infrastructure is required, and a single unit can meet the water requirements of between 250 and 400 people at an estimated cost as low as USD $1.50 per person per year.

After prefiltering with two washable bag filters of 25 and 10 microns (Fig. 24), disinfection is achieved with use of a 20 watt UV_{254} lamp (dose of 40 mJ cm^{-2}). A solar panel of 80 W is used so that it can perform independently even in a remote area without access to grid energy. The unit has a total weight of 44 kg with dimensions of 54 × 75 × 140 cm (excluding solar panel). Flow rate is approximately 5 LPM. Storage capacity is 100 L. A regular 12 V car battery can be used for backup power during the night and is charged by the system's solar panel.

12.4. Challenges and opportunities

Twenty-three Naïade units have been installed at schools (Fig. 25) and small hospitals in Rwanda and maintained by the Impala Foundation, and some of these units have been operational for over 12 years now. Units were financed by the Dutch Soroptimists organization.

The biggest challenge is financing the purchase of units and maintenance. This has been the case in all countries where Naïade systems were installed, within Africa, Asia and South America. Neighboring schools using chlorine have indicated that they have a strong wish to switch over to UV, due to costs and work instructions.

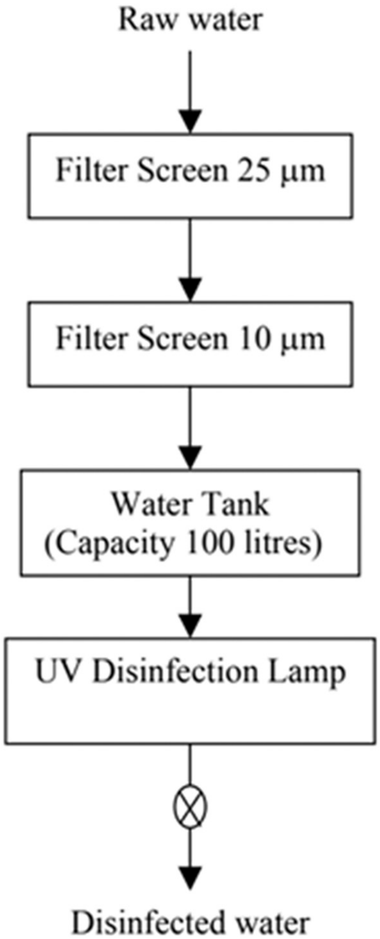

Fig. 24 Two bag filters prefilter water before UV disinfection.

12.5. Lessons learned

Technically, the Naïade system has proven to work as it has been designed and has been tested by UNESCO IHE: "*Under the conditions tested, it was found that Naiade UV disinfection system could remove total coliform and E. coli from the raw water up to 3 to 4 log removal*".

Fig. 25 A Naïade (on the left) and rainwater harvesting tank on a primary school in Kigali, serving 240 children and 20 staff members.

At some schools, it was reported that within two weeks after installation of a Naïade system, approximately 40% more children attended school because of a decreased incidence of chronic diarrhea.

In Rwanda, units are installed in Gisenyi, Musasa, Kigali, Muhanga, Musanze, Huye, Kayonza, Umutara, Kibungo, Nyabihu, Nyirangarama, Nemba, Nyamata and Rwamagana, serving treated water to over 27 300 students.

The most challenging topics remaining include:

• Financing units and maintenance.

• Local attendance for installation, maintenance, service and education.

13. The bring your own water treatment system (Rwanda)

13.1. General data

Type of Project Safe and affordable drinking water
Location Rwanda
Project Period 2005 to ~2015
Scale 10 LPM community-scale system
Affiliation & Contact University of Colorado at Boulder chapters of Engineers Without Borders (EWB-CU) and the Johnson Space Center (EWB-JSC), and Manna Energy Limited Prof. Evan Alexander Thomas, ethomas@colorado.edu
UV System Low Pressure UV, 40 W, (R-Can Environmental Sterilight, now called VIQUA)
Implementation Challenges for UV • High-volume throughput using mostly locally available parts • Requires importation of UV lamps
Select Solutions to Implementation Challenges • Coupling system with other technologies – drip irrigation, lighting, biogas generators • Strong relationships with community leaders enabled recruitment and training • Liaising with importers for UV lamps • Free-of-charge system was a component in adoption

13.2. Background

The Bring Your Own Water treatment system (BYOW) was developed between 2005 and 2010 by the Engineers Without Borders-USA. Chapters at the University of Colorado Boulder and the NASA-Johnson Space Center. Two complete systems were installed in the Muramba and Mugonero, Rwanda communities,[52] located in remote and mountainous locations that are both densely populated and economically underdeveloped.

Both Muramba and Mugonero were faced with frequently contaminated and untreated water from a range of sources, including piped water, harvested rainwater and surface water. All water sources were shown in initial testing to be contaminated with coliforms, some of them with *E. coli*, indicating human and animal fecal contamination, with levels of contamination fluctuating seasonally as a result of heavy rainfall. Testing also showed turbidity above advised values, which can be associated with higher levels of disease-causing organisms attached to particulates. The goal was to reduce exposure to contaminated water causing diarrheal illnesses by treating the water using the BYOW system.

13.3. Technology description

Without a single, fixed water source or reliable electricity in either of the target communities, communities required an off-grid system capable of producing safe drinking water from input water with a broad range of qualities, and the system also must be maintainable in these conditions. To meet this challenge, engineers combined several known technologies to produce a novel solution: a) a gravity-feeding inlet bucket; b) an up-flow gravel roughing filter; c) a self-filling tank for filter backwashing; d) a pressurized rapid sand (gravel-sand-pumice) filter; and a e) photovoltaic-powered UV sanitation subsystem with an electronic timer and valve.[53] The entire system is gravity fed. By leveraging existing structures and natural elevation features, it could be constructed with a ~3 m height difference between stages b), c) and d), which provides the necessary inlet pressure for the use and backwash of the filtration stage d), as shown in Fig. 26. The energy provided for the 40 W UV sanitation subsystem is provided by a 50 W or 102 W photovoltaic solar panel.

The BYOW system is capable of treating water at 10 LPM, as was shown in long-term testing in Houston, Texas, where activated sludge from a sewage plant was used as an input. In this extreme case, the system was capable of reducing turbidities of 70 NTU to below 1 NTU, and 3000 CFU mL^{-1} to below 2 CFU mL^{-1}. In the field, a maximum of 4.65 NTU was reduced to below 2.25, and a maximum of 63 CFU mL^{-1} to zero, with the exception of one case, where CFU mL^{-1} was reduced to one.

The lamps in the UV system are rated for 365 days of constant use, so if the system is used for less than six hours per day, it can be inferred that each lamp will last four years (neglecting lamp cycling impacts). The lamp is installed within a quartz sleeve.

13.4. Challenges and opportunities

Implementing a humanitarian solution in an effective and sustainable manner requires several key non-engineering conditions to be met: a) technology adoption by the community; b) the sourcing of materials without relying on long-range transport; and c) the training of local personnel to operate maintenance protocols.

In order to ensure the technology adoption by the local community, local community leaders were recruited to organize the installation of the system, and the BYOW units were implemented alongside other technological solutions, such as drip irrigation, solar-powered lighting and computers, and biogas generators. In Mugonero, the installation of the BYOW system was supplemented with the installation of six 10 m^3 rainwater collection tanks. The relationship with community leaders also ensured reliable recruitment and attendance for maintenance training sessions conducted by the engineers.

To ensure minimal reliance on non-local materials, a trade study was carried out as part of the design phase, wherein alternative solutions were compared with respect to (among other parameters) the local source-ability of the required materials. By liaising with an importer in Kigali (near the communities) with whom community leaders have an existing commercial relationship, the means of sourcing replacement UV lamps was secured – by far the most challenging of the components to source.

The systems were installed for free-of-charge use, although future BYOW systems could operate a pay-per-use business model. Assuming the worst-case situation in the replacement of a lamp every six months at a cost of ~\$100, the running cost per liter for each BYOW system was \$0.027. The initial installation of the system cost about \$5000 and it was designed to operate for 10 years before it would require major refurbishing, rendering the likely cost per liter at \$0.10. If a typical worker earns \$1 and uses 4 L of clean drinking water per day, the cost of drinking water from the BYOW system is less than 0.3% of income. However, users reported that the free-of-charge aspect of the BYOW systems implemented was a strong component in their adoption of the technology.

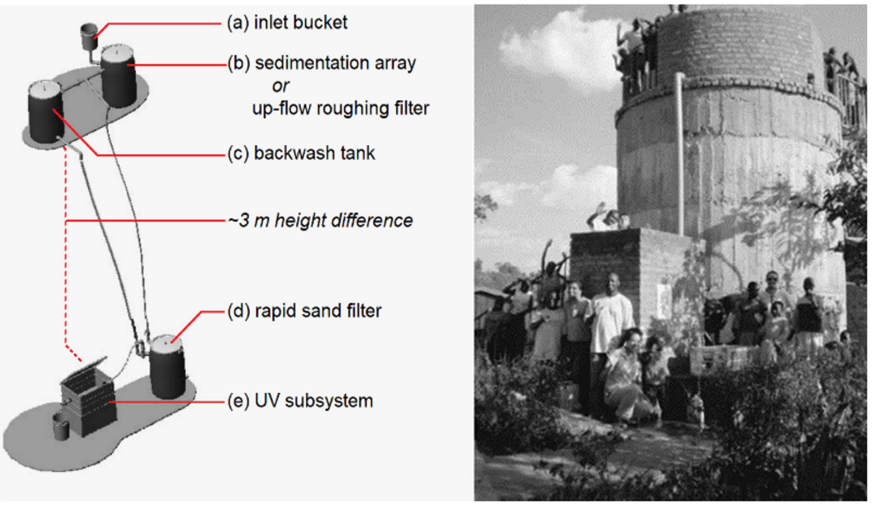

Fig. 26 A schematic of the BYOW system (left) and photo of the system installed in Mugonero (right).

13.5. Lessons learned

The findings from this project provide several important lessons for the implementation of water treatment systems in economically under-developed communities. Firstly, designing a technology that is maintainable economically and sustainably is paramount, prioritizing the elimination of biological contamination *via* UV disinfection and then working backward to design a full system. Secondly, community adoption is contingent on a number of factors outside of water treatment, the provision of other technologies contributing to a perception of a water treatment technology forming part of a suite of community-enriching technologies that is greater than the sum of its parts. Lastly, community adoption is vital not just for use, but for maintenance and reporting, which have been vital for the continued use of the BYOW systems in both the Muramba and Mugonero communities. These water treatment systems were known to be maintained by the communities for at least 10 years.[54]

14. Carbon-financed rural water treatment (Rwanda)

14.1. General data

Type of Project Drinking water
Location Rwanda
Project Period 2007 to 2010
Scale Up to 100 LPM community-scale system
Affiliation & Contact Manna Energy Limited and Portland State University Prof. Evan Alexander Thomas, ethomas@colorado.edu
UV System Low-pressure UV, 80 W (R-Can Environmental Sterilight line)
Implementation Challenges for UV • Installation required extensive engineering and project management • Funding through weak carbon credit markets not a sustainable business model to provide sufficient revenue for O&M
Select Solutions to Implementation Challenges • Consider ultrafiltration for pretreatment • Future potential for sustainable financing through carbon finance as market develops

14.2. Background

The Manna Energy Limited and Portland State University in-line water treatment system was developed as an evolution of the BYOW treatment system in Rwanda between 2007 and 2010. This in-line treatment system was designed to provide a much higher volume of water for communities and schools, up to 100 LPM. The system design was motivated by a partnership with the Rwanda Ministry of Education and designed to be fully funded and maintained through the generation and sale of United Nations carbon credits, offsetting both the actual use and demand for firewood for water boiling. This technology was deployed as the first-ever demonstration of this business model globally.

Fig. 27 An example of the Manna Energy Limited water treatment system. The system is installed in-line with existing water pipes. On the right is an elevated backwash tank. In the center is a gravel filter and a pressurized sand filter. On the left is the solar photovoltaic-powered UV system.

14.3. Technology description

The Manna Energy Limited water treatment system was designed to be fully in-line with the existing water supply infrastructure among rural, mountainous communities in Rwanda. As such, the system was required to accommodate highly variable input flow rates, water quality and high demand.

The design solution is installed in-line with existing water pipes and included an elevated backwash tank, a gravel filter and a pressurized sand filter, followed by a solar photovoltaic-powered UV disinfection system (Fig. 27).

The UV system included two Sterilight UV lamps, a RealTech UVT sensor, a flowmeter and a valve. The electronic controller, designed by Manna Energy Limited and Portland State University engineers, monitored UVT and flowrate. It turned the smaller UV lamp on for low flowrates and clear water and the larger UV lamp on for higher flows and lower water quality; the flowrate was controlled with a valve to maintain a minimum UV residence time (Fig. 28).

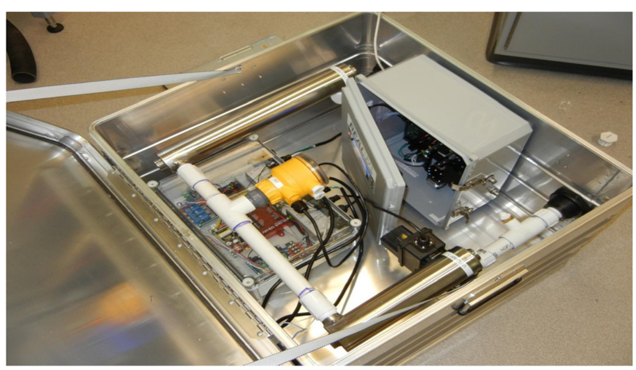

Fig. 28 The UV system included two Sterilight UV lamps, a RealTech UVT sensor, a flowmeter and a valve. The electronic controller, designed by Manna Energy Limited and Portland State University engineers, monitored UVT and flowrate. It turned the smaller UV lamp on for low flowrates and clear water, then the larger UV lamp on for higher flows and lower water quality, and controlled the flowrate with the valve to maintain minimum UV residence time.

14.4. Challenges and opportunities

The system was highly capable of treating large volumes of water. However, each installation required extensive local engineering and project management, thereby limiting the ability to scale. Further, the work was funded through carbon finance, which at the time was a weak market.

14.5. Lessons learned

While UV disinfection systems are highly effective at water treatment, they do require electricity, pre-filtration and monitoring. As such, in many contexts, other water treatment systems may be more viable, cost-effective and fail-safe, including ultrafiltration membrane systems.

15. UV waterworks 2.0 and 2.1: water disinfection in rural South Africa

15.1. General data

Type of Project Drinking water
Location KwaZulu-Natal, South Africa
Project Period 1997
Scale 15 LPM per unit (typically 3 units used in parallel)
Affiliation & Contact Energy Technologies Area, Lawrence Berkeley National Laboratory and University of California Berkeley Prof. Ashok Gadgil, ajgadgil@lbl.gov David Greene and Dr. Anushka Drescher
UV System Low-pressure UV, UV Waterworks
Implementation Challenges for UV • User operation: mistakenly assuming the device was turned on when it had been disconnected for maintenance • Public sector mobilization and financing
Select Solutions to Implementation Challenges • Simplify systems to reduce maintenance requirements • Electrically-controlled flow control valve installed at the inlet, which would open only when the UV system was supplied with power. • Photo sensors to monitor the UV lamp output and the UV transmittance

15.2. Background

The initial UV Waterworks implementation in Bhupalpur, rural India, was described in case study #5. The revised compact design ("UV Waterworks 2.0") then was pilot tested in the children's hospice, Lily of the Valley, in a rural area adjacent to Durban in South Africa (Fig. 29). A second pilot test in South Africa was conducted at a health clinic outside the town of Dundee in KwaZulu-Natal. The Natural Resources Defense Council (NRDC) was key to launching this effort successfully, and USAID provided financial support *via* LBNL, as did the United States Department of Energy.

15.3. Technology description

The design team created a device to disinfect water using the equivalent of a 60 W light bulb at a cost of two cents per ton of water treated, treating 15 LPM, enough for 500 to 1500 people, depending on how many hours the unit is operated daily and on how much drinking water per person is consumed daily. In laboratory testing with *E. coli* in dechlorinated tap water in Berkeley, UV Waterworks achieved a reduction in colony forming units (CFU) of *E. coli* by a factor of 99.9999% (*i.e.*, a million-fold reduction; *i.e.*, 6 log inactivation). UV Waterworks was tested by third-party laboratories to ensure it can kill 15 different pathogenic bacteria (including *Campylobacter jejuni*, *Shigella*, *Salmonella typhi*, *Vibrio cholerae* and *Escherichia coli*) and multiple pathogenic viruses (including rotavirus and poliovirus), and also cysts of *Giardia*. Specific capabilities of the device include:

1. Works with unpressurized water.
2. Deactivates pathogenic bacteria and viruses in water with turbidity of up to 30 NTU.
3. Does not need a trained operator.
4. Maintenance is minimal and infrequent (every six months).
5. Rapid disinfection (water passes through the unit in 12 seconds).

Fig. 29 UV Waterworks 2.0 unit installed on the exterior wall of the kitchen at the Lily of the Valley HIV-Hospice near Durban, South Africa.

15.4. Challenges and opportunities

The pilot testing at the Lily of the Valley led to one very important lesson. The device was installed on the exterior wall of the kitchen, and the water flow was controlled from inside the kitchen. To ensure that anyone could easily verify that the UV light was working, the design team had provided a window that would allow safe viewing of the UV lamp through a clear polycarbonate window. Polycarbonate blocks all UVC but allows transmission of the blue visible light. Thus, the operation of the UV lamp (and thus the active disinfection of the water) could be verified easily and continuously, per the design intent. However, the exterior installation at a large height defeated this design intent.

It turned out that once, prior to opening the device for routine maintenance, the local electrician had disconnected the power to UV Waterworks; however, the electrician overlooked reconnecting the power when the maintenance

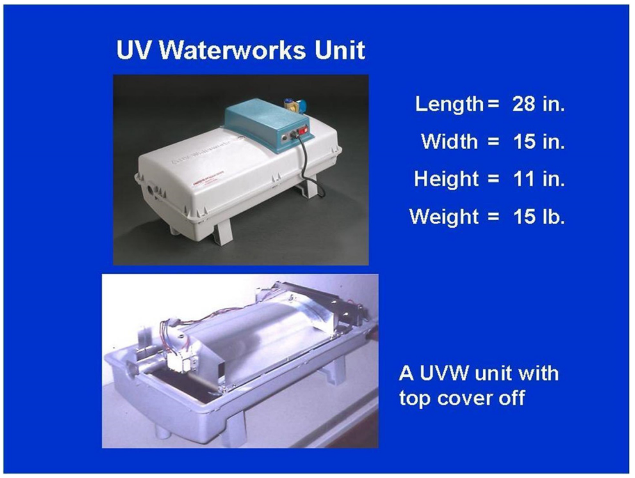

Fig. 30 UV Waterworks 2.1 (top picture) showing the piggyback electronics box on the exterior of the main compartment. The control valve is visible just behind the electronic box. The lower picture shows inside the UV Waterworks, with the top cover removed. The viewing tube and its polycarbonate window are visible on the left wall of the opened device.

was completed. Since the hydraulics (water inlet and outlet) were decoupled from the power supply to the lamp, the kitchen staff continued to use the device, mistakenly thinking that the water emerging from the faucet was disinfected. This problem was discovered and corrected upon a subsequent visit to the hospice.

The corrective design change immediately implemented in the design (now called UV Waterworks 2.1, Fig. 30) was the addition of an electrically controlled flow control valve at the inlet, which was normally off and would open only when the device was supplied with power. Additionally, two photo sensors added inside the UV Waterworks also controlled this valve. One photosensor monitored the UV lamp itself, and the other monitored the UV transmittance of the water being treated. Unless the UV lamp was on and the UV transmittance of the water also was adequately high, the inlet valve would remain closed. This large electromagnetic valve consumed an additional 20 W of electrical power, raising the total power consumption from 40 W to 60 W. This is the design that was mass produced by the industrial licensee after the year 2000 for commercial implementation.

15.5. Lessons learned

The organizational component of the public sector approach in this case provides several important lessons. Despite a well-organized, half-day executive dialogue roundtable, sponsored by USAID and attended by 21 representatives from UNICEF, WHO, several NGOs and other interested organizations, the next steps in development remained undefined, largely due to the lack of an established route to deployment. Without a consensus on how to deploy affordable water treatment technology in under-funded communities, money cannot be spent, and systems cannot be installed. This organizational and financial challenge with respect to public sector involvement is as apparent in 2022 as it was 1996.

In sharp contrast, the business model undertaken to bring the device to market through the private sector was highly successful. Leveraging the inventors' novelty through a patent-licensing agreement and technical expertise through a continued development partnership, funding has been secured in an amount that is an order of magnitude higher than the initial public funding. Obstacles to deployment in the hands of commercial partners in this case are beyond the scope of this paper.

The technical benefits of simplifying a device in order to reduce maintenance requirements were evident from the first case study; results that teach elegance over complexity in design. Similarly, appropriately strong community engagement was highly successful in effectively adapting the technology, presenting yet another positive lesson in collaborative development.

In conclusion, an innovative UV disinfection technology adapted for the under-developed economy was developed, tested, patented and licensed. The contribution to the general field has been significant, but public sector organizational challenges have hindered widespread deployment.

15.6. Acknowledgments

This project was made possible thanks to seed funding and support from the Energy Efficiency Program of USAID that spanned from 1995 to 1998.

16. UV treatment in rural healthcare facilities in northern Tanzania

16.1. General data

Type of Project Potable water treatment
Location Geita region in northern Tanzania
Project Period 2019 to Present
Scale 1 m^3/day 0.69 LPM (maximum capacity of 10 m^3/day) per system
Affiliation & Contact WaterAid Tanzania and University of Toronto Karlye Wong, karlye.wong@mail.utoronto.ca Prof. Ron Hofmann, ron.hofmann@utoronto.ca
UV System Low-pressure UV
Implementation Challenges for UV • Lamp burnout and damaged electrical wires and components • Poor user-focused design: difficult to inspect and clean system and UV lamps • Poor cleaning of rainwater harvesting system and quartz sleeve led to significant fouling
Select Solutions to Implementation Challenges • Improvement of operation, maintenance and inspection protocols • Training of community operators • UV reactor and hardware must be enclosed from environmental factors

Table 5 Locations of health clinics

Health clinic	Population
Kharumwa	27 093
Nkome	44 003
Kashishi	20 866
Nyangh'wale	15 323
Nyugwa	15 502
Bukwimba	18 415
Total	*141 202*

16.2. Background

In Tanzania and other developing countries, access to water, sanitation and hygiene (WASH) services continues to impact child survival and health. The incidence of preventable, waterborne diseases and diarrhea are responsible for 8% of deaths in Tanzanian children under five years of age.[55] Furthermore, poor WASH contributes significantly to malnutrition – approximately one third of young children are stunted. This poses a financial burden, whereby Tanzania spends 70% of its health budget on preventable WASH-related diseases.[56] While 45% of rural healthcare facilities (HCFs) have access to basic water services on premises,[57] the safety of the water being supplied and used in healthcare facilities remains a matter of critical concern. About 60% of HCFs had water supply systems that are categorized as high-risk, breaching WHO standards, and showing high degrees of unsafe microbial contamination in sample water.[58]

Without adequate WASH treatment, homes, schools and health centers become breeding grounds for diseases that kill children and threaten their ability to grow. Tanzania is one of seven countries with the highest disease burden caused by cholera in Africa.[59] The country suffers from late detection of cholera and outbreaks due to non-existent water treatment and weak surveillance systems, particularly in HCFs.[60]

16.3. Technology description

Originally, this project was part of a much larger public health project to address high levels of maternal and newborn mortality at hospitals. This intervention consists of seven solar-powered ultraviolet (UV) rainwater harvesting (RWH) systems in HCFs in the Geita region in northern Tanzania, serving a catchment region of over 130 000 people (Table 5). This was funded by an international agency and implemented by an NGO in 2019.

In this instance, rainwater harvesting (RWH) was used as a water source due to the lack of available groundwater and surface water in the area. Rainwater is known to be subject to contamination from collection surfaces and storage – bird and animal feces, tree waste and air pollution. At each hospital, rainwater was collected from a large rooftop catchment area. Through a series of gutters, the rainwater passed through a first flush diverter and wash-out chamber, which removed dirt, debris and leaves. The water was then stored in a 100 m^3 underground storage tank. A solar-powered pump brought the rainwater into a 10 m^3 raised storage tank. Water then flowed through a 25 W low-pressure UV lamp into the hospital facility for multiple uses for staff and patients in operation rooms, doctors' offices, bathrooms, *etc.* (Fig. 31). The UV lamp was powered by a 125 W, 12 V solar panel, which charged a 12 V lead-acid battery.

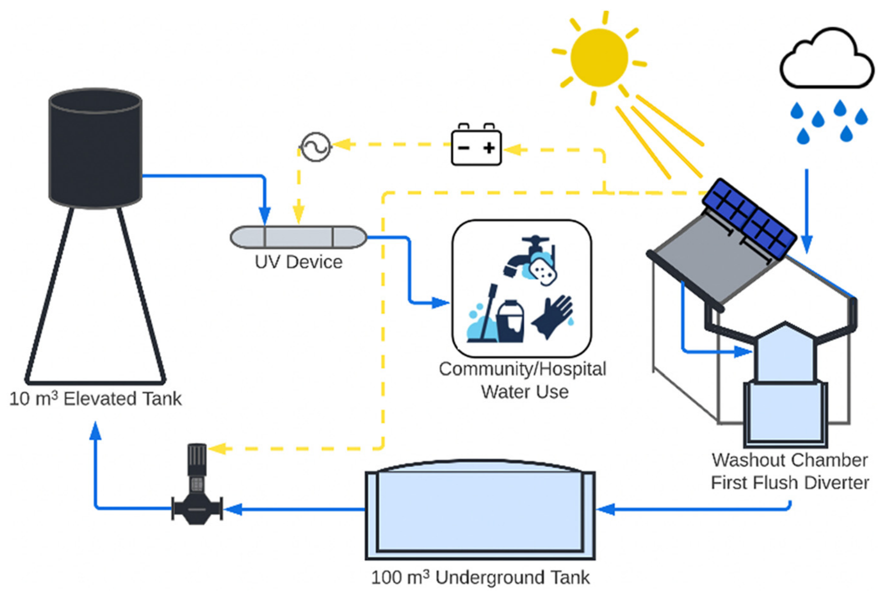

Fig. 31 UV rainwater harvesting (UV RWH) system.

16.4. Challenges and opportunities

Following the installation of the UV RWH system, the hospitals observed a significant drop in waterborne illnesses and increased satisfaction from service providers from the facility. They reported increased confidence in their work and satisfaction with their roles due to improved cleanliness of their facilities and the reduction in common infections.

After 18 months, an inspection of the six healthcare facilities observed that three of seven lamps were not functional at the time of visit; one lamp had burnt out while two were not functioning due to electrical issues. Two of the malfunctions were due to poorly designed electrical components. Poor housing, protection and monitoring of the systems resulted in damaged wire connections and hardware caused by birds and overheating of components due to poor cleaning. The plumbing design was not conducive for regular cleaning and inspection of the UV lamps. Furthermore, the UV lamps themselves did not provide clear user feedback of their status. This resulted in lamps that overheated from being always on or lamps that were not functioning due to burn out or simply being switched off.

The majority of the lack of functioning was due to poor technology transfer to staff throughout turnover, missing maintenance protocols and lack of awareness and understanding of UV function. This oversight was primarily seen through poor cleaning of rooftops and gutter systems, which may have contributed to the significant dirt and fouling on the quartz sleeve and interference with UV transmittance.

16.5. Lessons learned

To ensure sustainability of these projects in low-income settings, it is necessary to consider socio-economic perspectives, governance structures and community engagement. Implementation must be accompanied with contextualized approaches, technical expertise and a standardized, research-based approach to available and sustainable O&M. Strong research and key industrial and academic partnership from the global water and clean tech community may elucidate future social, commercial and tourism-related opportunities for investment. Growing this knowledge base and building the research would be able to support innovative monitoring and financing mechanisms for sustainability and future expansion of UV in Tanzania and beyond.

16.6. Acknowledgments

We acknowledge the funding support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC). The Geita District Council, the Nyangh'wale District Council, WaterAid, Davis & Shirtliff, Nesphory Sungu, Baraka Mbalaga, Peter Kwizela and Galus Komba.

17. UV LED demonstration unit in Uganda for drinking water disinfection

17.1. General data

Type of Project
Drinking water
Location
Gulu, located in Northern Uganda in the Western Uganda's Kyegegwa District
Project Period
2021 to Present
Scale
Health Center or Primary School, 3.5 LPM
Affiliation & Contact
African STEM Education Initiative, info@aseiug.org, and Aquisense, info@aquisense.com
UV System
UV LED, 280 nm, PearlAqua Automate, AquiSense Technologies
Implementation Challenges for UV
• Protecting the UV system from damage • Inconsistent power supply and potential power surges • User safety
Select Solutions to Implementation Challenges
• UV must be enclosed for protection • Integrate UV LED units into micro-factories to treat great volumes of water

17.2. Background

In Uganda, nearly 70% of the population is without access to clean water. Only half of the healthcare facilities treat water to make it suitable for drinking. Municipal water systems are rare and difficult to install, and bottled water is considered a luxury. The African STEM Education Initiative (ASEI) is an NGO whose goal is to provide Ugandan students with the resources needed to advance their knowledge in STEM, along with a secondary goal to provide clean drinking water to promote the lifelong health of children and communities in Uganda.

17.3. Technology description

The AquiSense PearlAqua Automate system was designed to provide a flowrate of 3.5 LPM. It is intended for point-of-use treatment. It is compliant with NSF/ANSI-61 for materials safety and uses a 280 nm LED. The PearlAqua was installed in series with a 5 micron filter or activated carbon filter to remove any particles. The LED is activated when a flow meter detects flow. The system is equipped with a performance indicator to alert the user of faults with the LEDs. The power for the 12 VDC/20 W PearlAqua system can come from solar electricity or a local power grid. For the installations in Uganda, the water was obtained from rainwater harvesting or groundwater, and it was first treated using bio-filters and cartridge filters (Fig. 32).

17.4. Challenges and opportunities

One challenge that was identified was the need to ensure the UV units and filters are enclosed to offer protection from damage by individuals who are not intended to operate the system. Accordingly, the UV units were installed in a locked case that could be

Fig. 32 ASEI and AquiSense Technologies water treatment and delivery system.

opened when the system needed to be checked. There is also a need to consider unreliable power quality in the local grid, such as overvoltage conditions, that could damage the electrical components (*i.e.*, the circuit boards). It must also be recognized that a UV system is an inherently electrical treatment system that must be placed next to water, so the power and the water must be well managed to limit the possibility of electrical shocks.

ASEI is exploring the opportunity to integrate the UV LED units into modular micro-factories, each with the ability to produce about 1500 L per day of treated water. These micro-factories can be leased to water vendors to supply treated water from central locations in communities.

17.5. System results and lessons learned

The system has been operational since installation. During that time, the influent *E. coli* (in some cases too numerous to count), were reduced to 104 CFUs per 100 mL by the filters, and further reduced to <1 CFU per 100 mL by the UV disinfection.

The consumers in this case study region are health conscious and had concerns with the use of chlorine. This case study demonstrates that, when integrated into an appropriately designed water treatment and dispensing system, UV disinfection can provide an effective treatment option free of oxidative chemicals.

18. The water-on-wheels mobile emergency water treatment system (United States and Ukraine)

18.1. General data

Type of Project
Potable and non-potable water treatment
Location
Kentucky, United States and Ukraine
Project Period
2021 to Present
Scale
55 m^3/day (per system), ~ 38 LPM
Affiliation & Contact
United States Environmental Protection Agency and WaterStep Dr. James A. Goodrich, Goodrich.James@epa.gov, Sr. Science Advisor, USEPA, Office of Research and Development, Center for Environmental Solutions and Emergency Response, Kurtis T. Daniels, Vice President, Director of Field Operations, WaterStep Mark Hogg, Founder and CEO, WaterStep Dr. Gregory Sayles, Director, USEPA, Office of Research and Development, Center for Environmental Solutions and Emergency Response
UV System
UV LED, 280 nm, Pearl Deca, AquiSense Technologies
Implementation Challenges for UV
• Awareness, knowledge, acceptance at government level
Select Solutions to Implementation Challenges
• Better integration of UV within the government's existing emergency protocols

18.2. Background

Following a natural or human-made disaster, a community's water treatment plant or distribution system may be rendered incapable of providing safe water to all or portions of its drinking water distribution system. The lack of safe drinking water can have serious effects on the public's health.

The water-on-wheels mobile emergency water treatment system (WOW Cart, Fig. 33) is designed to provide treated water during such a response and recovery period. It is designed for deployment anywhere in the world and can provide potable water using sources ranging from raw water to compromised water from distribution systems. Oftentimes, deployments are conducted in conjunction with local nonprofit organizations from the impacted community. WaterStep, a Louisville, KY nonprofit and fabricator of the WOW Cart often works with State or Federal agencies coordinating deployments with local/nearby water utilities or other nonprofits.

Recent deployments of the WOW Cart include:

- Western Kentucky, following multiple tornadoes in December 2021.
  - Graves County Public Health Department
  - Mercy Chef Mobile Kitchen

Fig. 33 WOW cart.

Fig. 34 WOW cart providing water for mobile showers in Western Kentucky.

  - Dawson Springs 4H Camp
- Eastern Kentucky, following flooding in multiple communities in August 2022.
  - Perry County, HomePlace Community Center
  - Perry County, Buckhorn Children's Home
  - Letcher County, Mayking Fire Department
  - Breathitt County, River Caney Staging Area
- Ukraine in Summer 2022.

18.3. Technology description

UV LED technology has been integrated into the WOW cart drinking water treatment train, essentially replicating a conventional water treatment system with the added benefit of UV disinfection. Unit processes include filtration, GAC adsorption, UV LED and chlorination. As demonstrated during Hurricane Maria in Puerto Rico, emergency response was severely hampered by excessive road damage and debris blocking tractor trailers from being able to deliver bottled water or quickly repair the electric grid. The WOW cart was designed to address situations where communities are without power and with limited access into the impacted area.

The WOW cart's design minimizes the footprint and weight, which can enable transportation in the back of a pickup truck and movement on-site by two people. The UV LED system also adds to the robustness of the system, minimizing any risk of damaging the device during transportation and operation. The on-site treatment of water also reduces the dependence on bottled water, which creates a solid waste disposal problem. Additionally, the WOW cart fills a niche that bottled water cannot address in terms of providing safe water for showers (Fig. 34), laundry, food preparation/clean-up and general sanitation, which could also include medical triage. It is also envisioned that WOW carts could be pre-deployed to critical institutions such as nursing homes, hospitals and prisons, where relocating residents presents a considerable health and financial risk.

The WOW Cart is 30″ wide × 48″ long × 42″ tall, weighs less than 500 pounds and produces up to 38 LPM (typically operated at 31 LPM, depending on the conditions of the filters). It can be operated off the grid using the supplied dual-fuel gasoline/propane generator or by plugging it into a normal wall outlet. There is no complicated mixing of chemicals, filter backwashing or large volumes of media to dispose of. The UV LED system (Pearl Deca) is manufactured in Kentucky, United States by AquiSense Technologies. It consists of multiple UV LEDs with a nominal wavelength of 280 nm and operates from a 24 VDC input. The UV disinfection capability provides an additional level of disinfection at a UV dose of 30–40 mJ cm^{-2} (wavelength unspecified), which complements the chlorination step in its ability to inactivate microbial contaminants (such as *Cryptosporidium* spp.) that chlorine is unable to address. The UV LED technology fits perfectly into this concept with a small footprint and simply monitors flow rate to turn instantly on at full power with flowing water, thus limiting fouling potential and ensuring an extended lamp replacement interval.

Volunteers without water treatment expertise can be trained quickly to operate the WOW cart. The UV LED system has NSF material compliance certification and requires almost no maintenance, thus adding to the ability of volunteers to provide safe water. It is expected that following deployment, the WOW Cart will be warehoused following complete drainage and drying out until needed for the next response. It can be purchased by government agencies, water utilities or other nonprofits from WaterStep. Monetary donations to the organization following disasters allows them to donate WOW Carts to impacted communities and other nonprofits.

18.4. Challenges and opportunities

One of the main challenges to the widespread adoption of mobile emergency water treatment in the United States, including UV, is not technological. It is the state-by-state approvals required. Another challenge is the training and staffing of volunteers and qualified personnel to operate the systems. One solution to acquiring pre-approvals and integration into the State or Federal emergency operations' standard operating procedures is under consideration; namely, the "Lily Pad" concept of pre-staging multiple WOW carts in communities across the state, available for deployment and operated by trained local water system operators. This is being developed in Kentucky. Awareness, knowledge and acceptance of inexpensive, easy-to-operate and deployable mobile water treatment systems at the government level is necessary for widespread adoption.

18.5. Lessons learned

Various deployments have successfully provided safe water for thousands of people to drink, bathe, wash clothes and prepare food. The addition of the UV LED technology has only improved the reliability and the quality of water being provided.

19. Year-long study of UV LED disinfection in rural Jamestown, Colorado, (United States)

19.1. General data

Type of Project	Bench testing and pilot demonstration in a rural drinking water system
Location	Jamestown, CO, United States
Project Period	January 2017 to February 2018
Scale	300-household water system, but the system treated a subset of volume that would be appropriate for approximately one household (0.5 LPM).
Affiliation & Contact	Design of Risk-reducing, Innovative-implementable Small-system Knowledge (DeRISK) Center, led by University of Colorado Boulder Prof. Karl Linden, karl.linden@colorado.edu Dr. Natalie Hull, nataliehull@boisestate.edu
UV System	UV LED, 280 nm, PearlAqua, AquiSense Technologies
Implementation Challenges for UV	• Turbidity > 1 and UVT < 90% from sand filter effluent during warmer months • No cleaning or maintenance of UV reactor for greater than one year of continuous operation
Select Solutions to Implementation Challenges	• UV LEDs useful with low mineral water to minimize fouling, chlorine use, and disinfection byproducts

19.2. Background

Most municipal drinking water systems in the United States range in size from very small to medium (97% of systems serve <3300 people). More violations and the ratio of health violations to total population served is much higher in small systems, indicating a disparity of greater health risk to those served by small systems. More accessible, sustainable technologies and strategies of disinfection could prevent some of these health-based violations and protect the people served by the majority of these smaller systems.

A UV LED water disinfection reactor (the PearlAqua by AquiSense Technologies) was studied over a year-long demonstration test, and performance was compared side-by-side with an existing chlorination system at a small water treatment plant in Colorado serving about 300 people. As detailed further in Hull *et al.*,[28] the UV LED disinfection system was validation tested using MS2 bacteriophage inactivation over a range of flow rates and water UV transmittances. The reactor also was challenge-tested with MS2 periodically during the year-long demonstration. Over the bench testing and during the demonstration study in challenging conditions without any maintenance, the reactor demonstrated viral and bacterial disinfection efficacy and resilience, providing proof of concept for application of UV LED for municipal treatment.

Light-emitting diodes (LEDs) are non-mercury sources of polychromatic UV emission with promise as a sustainable solution for drinking water disinfection in small communities. Manufacturers and researchers have produced LEDs capable of emitting wavelengths across the UVC spectrum (200 nm to 280 nm) as low as 220 nm.[61] UV LEDs could be more sustainable than traditional UV lamps because they do not contain mercury, have lower power requirements, are more compact and are becoming more efficient as materials science advances.[23,26] Additionally, LEDs are capable of nearly instantaneous power-up, do not suffer from unlimited cycling, have long lifespans, are small in size and have higher power density than conventional mercury UV lamps.[62]

One objective of this research was to validate UV LED reactor disinfection performance at bench scale across a range of flow rates and UV transmittances to develop a predictive model for disinfection (Fig. 35). In the second objective, the LED reactor was installed in the first long-

Fig. 35 UV LED reactor disinfection performance was assessed under varying conditions at bench scale (left) to develop a predictive model that was used to assess performance during challenge testing after pilot installation (right).

term disinfection demonstration in a small drinking water system. The validation model was used to assess disinfection performance over time through periodic challenge testing.

19.3. Technology description

The reactor model 25G is an NSF International 61- and IP65-certified UV LED water disinfection system with a maximum operating pressure of 100 psi and a pressure drop at maximum flow (12 LPM) of 1.3 psi.[63] It is rated for operating in water temperatures ranging from 0 °C to 50 °C, connects with 1/2-in. (outer diameter female national pipe thread [FNPT]) fittings, weighs 3.3 lb, and measures roughly 6 × 6 × 6 in. for the entire system. The reactor operates in upflow orientation where water passes through an internal diffuser before irradiation, can be mounted with a spring-loaded bracket and is powered by a single cable from the UVinaire LED module to a standard outlet (120 V and 60 Hz). The power cable has a converter that supplies 12 V DC to the UVinaire, with 2.5 A maximum current and 26 W nominal power consumption. The UVinaire houses the internal electronics, fan, heat sink and array of LEDs that irradiate through a quartz window to the reactor interior. The outside of the UVinaire has two visible LED indicator lights coded for various electronic warnings to indicate the status of the system and LEDs. The UVinaire has an internal 4–20 mA current loop that can be used to measure the lamp life remaining or for remote monitoring and operation. Before testing, the total output power of the UVinaire was approximately 0.25 W.

The field site for the demonstration study was the drinking water treatment plant in the small mountain town (population ~300 and elevation ~7000 ft) of Jamestown, CO, United States. Surface water directly from James Creek or from a shallow infiltration gallery was slow-sand filtered before chlorination and distribution of approximately 38 to 208 m^3 per day, depending on seasonal demand. The UV reactor was installed on the outlet of the slow-sand filter and operated at 0.5 LPM in parallel to the existing chlorination system.

19.4. Challenges and opportunities

In this mountain system, temporal variations in snowmelt and precipitation (in the form of snow and rain) that increased stream flow were most closely related to temporal changes in UVT, with the lowest UVT in the spring coinciding with the beginning of snowmelt. Turbidity was not closely related to changes in UVT. Total coliform were detected at highest concentrations in filter influent when water temperatures were warmest in the fall. Total coliform in filter effluent followed a similar temporal pattern, with a much lower concentration (average = 5 CFU mL^{-1} throughout the entire year). Total coliform were detected only sporadically in UV LED and chlorinated effluent (six and five times, respectively, at <2 CFU mL^{-1}). *E. coli* were detected at low levels in filter influent and at lower concentrations in filter effluent, but never in UV LED or chlorine effluent, indicating effective disinfection by both processes of this fecal indicator.

19.5. Lessons learned

This first longitudinal demonstration study of a flow-through UV LED disinfection reactor indicated the resilience and disinfection effectiveness of UV LEDs, operated continuously for nearly one year with zero maintenance, with an estimated electrical cost of less than $25 to disinfect water flowing at 0.5 LPM, at an MS2 bacteriophage reduction equivalent dose (RED) by LP UV of at least 40 mJ cm^{-2}. Disinfection performance was maintained (and actually was better than predicted) even when turbidity of the influent was greater than 1 NTU. Longitudinal evaluation of the flow-through UV LED system provides data necessary for practical operation, design improvements and scale-up, allowing faster adoption in the future. UV LEDs could be particularly useful to help utilities with low mineral source waters to minimize fouling potential and maximize disinfection and public health protection while minimizing chlorine use and, therefore, disinfection byproduct formation potential. Future work should consider scale-up to meet flow demands of municipal systems and modifications for lower UVT water, such as wastewater and reclaimed water.

19.6. Acknowledgments

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20. Conclusions

This manuscript brings together a wide collection of case studies from various academic institutions, organizations and companies from countries around the world, demonstrating the implementation of UV-based water treatment in low- to middle-income, humanitarian relief and rural settings. We include the motivations, location, system specifications and, most importantly, the outcomes and lessons learned, all to expand public knowledge and to support additional projects around the world.

Most case studies described resulted in outcomes that immediately improved the water quality and positively impacted the population; however, in almost all cases studied, the long-term effectiveness of the UV intervention (*i.e.*, over years) was not tracked nor reported. Furthermore, several insights and persistent limitations were uncovered and should be considered and addressed in future projects. In general, the challenges, considerations, and limitations can be summarized into five categories, described in more detail below (Table 6): availability, water quality, system design, operation and maintenance, and social factors.

20.1. Availability

In order to be considered appropriate technology, the parts required for UV disinfection must be consistently available for the particular applications in a low- to middle-income, humanitarian relief, or remote setting. This includes availability of the UV lamps (mercury-based, light-emitting diode or other), replacement parts, the power supply, and any pretreatment systems. This requires both the physical availability of the components *via* a reliable supply chain as well as the economic availability, or affordability, of the system. Often, this can be challenging. For example, in the two case studies from Kenya, we learned about the logistical challenge of locally sourcing a charge controller or surge protector to prevent frequent lamp burnout (case study 8) as well as the economic challenge of affording a filtration and UV-based rainwater purification system that costs $200 a day in a community of subsistence farmers who are earning $1 per day (case study 7). For more information, please see case studies 3, 7, 8, 13.

Water projects in low-income and rural settings are often financed by private, donor and governmental funding (case studies 7, 10, 12, 14). These projects have also been driven through establishing partnerships and applying innovative business models (case studies 4, 13). Water supply and treatment systems can require a significant initial investment; however, it is also important to consider the long-term financing mechanisms required to operate and maintain the UV systems.

Table 6 Summary of case study challenges, considerations and limitations by category

Availability
• Affordability and funding • Supply chain for replacement parts • Costs for scaling up
Water quality
• Turbidity spikes • Chemical and biological fouling • Water quality monitoring
System design
• Location of the water system • Inadequate user-focused design • Necessity of a reliable energy source
Operation and maintenance
• Insufficient training and staff turnover • Irregular maintenance and testing • Little to no project follow-up
Social factors
• Building community trust and buy-in • Community consultation • Water supply institutions and regulations

20.2. Water quality

In some cases, the root cause of a treatment failure was related to deteriorating water quality, which led to insufficient microbial inactivation due to particles in the water absorbing the UV rays or shielding the microorganisms from UV inactivation. Several case studies mentioned seasonal variations in water quality, such as spikes in turbidity from precipitation events such as snowmelt in Canada (case study 1) or poor water quality in the oorani, or rainwater collection ponds, in India (case study 4). This was reported for both groundwater (case study 11) and surface water sources (case studies 1, 4). The most important water quality parameters to test for in UV water treatment system design are UV transmittance (UVT) and turbidity. Poor water quality can also lead to biological fouling or chemical scaling of the UV systems, which was reported not only in the wastewater treatment system (case study 6), but also in drinking water systems in India (case study 5) and Tanzania (case study 16) (case studies 1, 4–6, 11, 16, 19).

Ensuring that UV disinfection is effective often requires effective pre-treatment. The water treatment processes upstream of the UV device must condition the water for effective UV treatment, particularly for reducing turbidity and increasing UVT. This may include using pretreatment technologies such as filtration and ensuring the UV systems apply sufficient irradiance over time (case studies 2, 3, 5–11, 13–20).

Additionally, while UV disinfection inactivates microorganisms, post-treatment recontamination is a concern. Factors such as sublethal UV doses, shielding by particulates, and the lack of residual disinfectants can contribute to microbial regrowth. Bacteria may recover through reactivation from a viable but nonculturable state, DNA repair, or reproduction of surviving cells.[64] UV systems require a continuous power supply, and failures or reduced intensity can compromise disinfection, increasing contamination risk. Without residual disinfection, treated water is vulnerable to recontamination, especially in non-sterile or containers or unsanitary conditions. A substantial increase in *E. coli* contamination in treated water taken from storage containers and drinking glasses compared to water taken directly from the UV system effluent has been found.[50] Additionally, UV treatment does not remove suspended solids, which can shield microorganisms, reducing disinfection efficacy.[65] Pre-filtration can be used to ensure water clarity. Certain bacteria, such as Listeria monocytogenes, have shown recovery post-UV treatment under favorable conditions.[66] To reduce these risks, proper storage, regular maintenance of UV systems, and integration with residual disinfection methods like chlorination can help to maintain water quality.

Another challenge that was observed is the lack of monitoring of the system's operation and performance over time due to the cost of water quality analysis, especially microbiological counts. These rely on correct sampling procedures and proximity to an external laboratory. The tests are tedious as they involve sampling, transporting the samples to the laboratory, and analyzing and reporting the results, all of which can take more than 24 hours. Regular testing activities and training can also be a burden for the community and local operators. According to WHO guidelines and the EU Drinking Water Directive,[67,68] the *E. coli* and FC parametric value should be zero colony-forming units (CFU) per 100 mL, which is complex to analyze in many settings (case studies 1, 2, 8, 11 15). Nevertheless, in some of the case studies, researchers used field kits which were able to measure inactivation of *E. coli* and fecal coliforms in the field (case studies 2, 3, 7).

20.3. System design

System design includes both the overall design of the water system and the design of the UV disinfection system.

20.3.1. Overall design of the water system. The overall journey of the water from its source to its treatment to its point-of-use should be considered, and the distance between these steps should be reduced as much as possible to prevent contamination. Long distances between source to treatment or treatment to user create physical barriers, which may impede consistent daily use or encourage unsafe long-term storage, thereby introducing possible recontamination. The position of the water system can impede effective disinfection in two primary ways: (1) the distance from the water source to the UV system may add effort to achieving treatment, and (2) the distance from the UV system to the point-of-use can lead to recontamination, especially without secondary disinfection (case studies 4, 8, 11, 16, 18, 19).

Additionally, the energy required for powering the UV reactors can be sourced from a range of power sources, including grid, solar, and battery (case study 5). Some locations might have access to a consistent energy supply from an electrical grid; however, some case studies reported intermittent electricity which could result in a shutdown of the UV source (case studies 7 and 10) unless backup battery power was available (case study 1). In these cases, alternative energy supplies should be considered, such as solar panels, gasoline generators, batteries or using a hand pump to charge a battery. The maintenance and assurance of energy should be considered in the initial design and in the operation and maintenance plan (case studies 4, 5, 8, 9, 11, 12, 16, 18).

20.3.2. Design of the UV treatment system. When considering only the UV component of the water disinfection system, there are technical benefits of simplifying the UV device to reduce maintenance requirements; this was evident from the oldest case study included, which was implemented in 1994. Reducing the moving parts and ensuring that a user can easily verify that the UV light is functioning is important. If the systems are too difficult to operate, they will not be used (case study 16). In an ideal design, the user will be able to tell whether the lamps are powered on or off, the device will stop water from flowing through it in the event of a light source failure, and the user would be able to easily operate and clean the system. Additional operational solutions may include alarms, sensors and back-up electricity sources, trained local operators, and the use of local UV equipment suppliers or importers (case studies 3, 4, 7, 15–17, 19).

In general, across the 19 case studies, there was a lack of consistency in how the UV systems were characterized and in the metrics that were used to demonstrate that the systems were performing adequately. For example, UV lamp intensity and UV dose (or Reduction Equivalent Dose, RED), log-inactivation and the target microorganism, lamp fouling and scaling, and validation testing protocols are commonly-used to characterize the efficacy of large centralized UV systems.[25] However, this information was either not tracked or not made available in several case studies. This may be a result of how new UV technology is compared to more established forms of disinfection (such as chlorination), the complexity of UV disinfection systems, and the lack of available guidance on UV system design and operation for decentralized systems.

20.4. Operation and maintenance

Several case studies reported the effect of poor operation and maintenance on the sustainability of the water disinfection system (case studies 2–6, 8, 12–16). This could be related to insufficient training such as not having enough people in attendance when the systems were installed (case study 12), having lack of trained personnel available (case study 5), lack of funding for operation and maintenance, or high staff turnover (case study 2). This challenge is only exacerbated in cases where the system is located at a site with inconsistent year-round usage, such as a school (case study 2).

In some cases, however, the challenges discussed in the previous section can be overcome with an effective Operation and Maintenance strategy. Examples of required regular maintenance activities include inspections, lamp replacement, quartz sleeve cleaning, and pretreatment servicing. It is also important to consider all factors of maintenance and properly define protocols, roles and responsibilities, professional servicing as well as sustainable financing for operation and maintenance costs (case studies 1, 2, 4–6, 8, 12–16, 18).

Various UV LED water treatment systems incorporate flow control valves managed by UV dose, UVT or water flow rate to optimize disinfection (case studies 1, 15, 17). UV monitoring systems detect decreases in UV intensity and lamp failures through UV light monitors, sensors, and alarm systems (case studies 6, 8, 13, 15). Internal current loops provide real-time system status and lamp life tracking (case study 19). These integrated control and monitoring mechanisms enhance system efficiency, reliability, and fault detection, ensuring effective decentralized water treatment.

It is important to follow up on the project post-implementation, not only from the technical side, but also by conducting interviews or surveys with users to address pain points at the intersection of the technology and the users (case studies 1, 2, 16).

20.5. Social factors

Community adoption and long-term use were affected by several social factors, such as coordination with local governments, public trust and the public perception of water quality (case studies 1, 2, 13, 16, 17). Having existing governance arrangements for the water system, or robust water service or business models that the UV system will operate within, as well as clear regulatory standards that the system must meet were reported to be helpful in enabling long-term use and maintenance (case studies 2, 3, 9, 18). Community consultation and engagement were helpful for identifying initial issues with the system, identifying potential strategies for operations and maintenance, as well as for building shared ownership of the system. Several case studies noted that ownership and public trust built through this process was important for improving use of the system and could also be helpful for finding local resources and local staff for maintenance, water quality monitoring and reporting (case studies 2, 4, 5, 9, 10, 13, 15, 16, 18).

This manuscript serves as introductory material for program managers who are considering UV as a technology; referencing these examples may provide inspiration while also preventing some of the common mistakes. This compilation, along with the associated map at **http://www.iuva.org/UN-Sustainable-Development-Goals-Task-Force**,[34] could also serve as a point of connection between future practitioners. We intend for the map to be an evolving document to which more case studies will be added over time. We hope that this paper and the case studies within will provoke discussions on what the water sector needs to advance in the adoption of UV technologies in low-resource settings.

Author contributions

The manuscript was conceived by N. Moore, D. Pousty, and H. Mamane. Manuscript coordination and leadership were provided by S. Beck and N. Moore. Case study integration and modifications were done collectively by the entire team. The manuscript was drafted by N. Moore, S. Beck, D. Pousty, H. Mamane, R. Hofmann with contributions from D. Ma and R. Higbee. The interactive map was designed by A. Pras.

Conflicts of interest

Authors Pousty, Ma, Hofmann, Higbee, Mamane and Beck were involved in the implementation, data collection, or writing up of some of these case studies.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and from the International Ultraviolet Association at **https://iuva.org/UN-Sustainable-Development-Goals-Task-Force**.

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