APPLICATIONS AND ACCEPTANCE OF SOLAR UV TECHNOLOGIES FOR DRINKING WATER DISINFECTION IN LOW-INCOME SETTINGS

by

Margaret M. Busse

A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Lyles School of Civil Engineering

West Lafayette, Indiana

December 2021

THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Ernest R. Blatchley III, Chair

Lyles School of Civil Engineering
Division of Environmental and Ecological Engineering

Dr. Amisha Shah

Lyles School of Civil Engineering
Division of Environmental and Ecological Engineering

Dr. Zhao Ma

Department of Forestry and Natural Resources

Dr. Chad Jafvert

Lyles School of Civil Engineering
Division of Environmental and Ecological Engineering

Approved by:

Dr. Dulcy M. Abraham

ACKNOWLEDGMENTS

I would like to thank Dr. Ernest R. Blatchley III for his support of this work and my goals throughout my graduate studies. I would also like to thank the members of my committee, Dr. Amisha Shah, Dr. Chad Jafvert, and Dr. Zhao Ma for their support of this work. I also could not have completed this work without the support of my mentor, Dr. Larry Nies.

My gratitude goes to all of my collaborators. These include Mark Jongewaard for his help with Photopia experiments conducted in this work, Dr. Melissa Brindise and Dr. Pavlos Vlachos for the collaboration on developing a blood-analog fluid, Jake Hawes for his contributions to the LCA work, and the Water Supply in Developing Countries course and all of its participants.

I would also like to thank my fellow grad students which include lab mates, Dr. Lester Lee, Dr. Yousra Ahmed, Xing Li, Rachel Gehr and previous office mates Kuhn Huang and Mahsa Modiri-Gharehvaren.

A special thank you to the organizations and communities that allowed me to conduct my fieldwork. In Kenya this includes AMPATH, Maji Safi, Alfred Lagat, and the primary schools with which we worked. In the Dominican Republic, this includes again our partnering primary schools as well as Tony Pena.

This work could not have been completed without the financial support received from many organizations. For the work conducted in Kenya, this includes the Trask Fund, the Borlaug Fellowship, the Andrews Environmental Fellowship, and numerous Purdue Service Learning grants. For the work in the Dominican Republic this includes Rotary West Lafayette (with special thanks to Jack Kelley), Rotary International, Rotary Santiago, Dr. Scholl Foundation, and again multiple Purdue Service Learning Grants.

I would like to thank the professors and organizations around Purdue that helped fund me as a graduate student. This includes Dr. Nies for allowing me to be the graduate TA for the CE/EEE 355 course, and to all of the peer teaching assistants for all of the feedback and support. A very special thanks to all of my colleagues at the Academic Success Center, especially Dr. Karen Jacobsen, Katie Dufault, Jannuel Cabrera and Marquetta Straight. Thank you to the SURF program, and the USAID LASER-PULSE program.

Finally, I would like to thank my family for always being a source of support and healthy distraction. And to Melissa Brindise for always believing in me – I could not have done this without you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Access to potable water has been identified as a basic human right, yet it is estimated that 2.2 billion people worldwide do not have access to safely managed drinking water. Many of those without access live in regions of the world with abundant sunlight, which can be utilized both directly and indirectly to disinfect drinking water. Directly it can be used in solar water disinfection (SODIS) applications, and indirectly it can be collected by solar panels to power commercially available UV reactors. Herein, we study the potential for direct and indirect water disinfection technologies to be used and adopted in developing countries, with specific insight into their application in the Dominican Republic and Kenya.

The amount of available ambient solar UV was both measured and modelled to inform design and modelling of treatment systems, and to understand whether real-time monitoring of ambient UV is required for the operation of systems directly utilizing UV for disinfection. The model both over- and under-predicted measurements of ambient UV, and did so at inconsistent rates, most likely as a result of cloud cover. This indicates that real-time monitoring of ambient UV would most likely be needed for disinfection methods directly using solar UV for inactivation in order to ensure water was always dosed properly.

The amount of available ambient solar UV was input into a raytracing model (Photopia, LTI Optics) to simulate the amplification of solar spectral irradiance within a continuous-flow compound parabolic collector (CPC). This informed design improvements that allowed for an increase in flow rate through the system, which was supported by field testing of the reactor. Further, two commercial UV reactors, one utilizing a low-pressure (LP) lamp and the other utilizing an LED source, were tested in the lab to verify their ability to inactivate *S. typhimurium* LT2. The LP-based device outperformed the LED-based device, which was unable to achieve over 2-$\log_{10}$ units of inactivation under any of the studied conditions.

A life cycle assessment was conducted to assess the environmental impact of the three studied UV reactors against traditional chlorination and water delivery methods. Chlorine had the lowest impact in every category under all of the studied conditions, but there have been many barriers reported on the lack of adoption of chlorine. So the next lowest impact technology was evaluated at the community scale, which was the LP reactor. Therefore, the LP reactor was installed in study communities in both the Dominican Republic and Kenya. In the Dominican

Republic, the systems suffered from a lack of boots on the ground, and faced technical, social, and economic barriers to adoption. In Kenya, the project suffered from similar constraints, that did not allow for project assessment. This work not only addresses the barriers faced in both of these projects, but provides suggestions for improving similar projects in the future.

CHAPTER 1. INTRODUCTION

1.1 Introduction

The United Nations (UN) has defined Sustainable Development Goals (SDGs) to address global challenges, with plans for implementation by 2030. SDG 6.1 defines universal and equitable access to safe and affordable drinking water for all, as measured by the proportion of population with available, safely managed drinking water services. In 2017, 71% of people globally were estimated to use safely managed water services. However, in developing countries this number dropped to only 35% . This difference is often a result of regional disparities in both climate and wealth. For example, tropical areas have a higher prevalence of disease and more difficult terrain for agriculture (Sachs et al., 2001). As a result, although nearly 40% of the world's population lives in tropical areas, only about 17.4% of the world's gross national product (GNP) is generated in those areas. Moreover, disparities of wealth strongly correlate to access to safe water services on both country and community levels, where the rural poor have less access to and often lower quality water. For example, in Angola, when dividing the country into quintiles defined as poorest, poor, middle, rich, and richest, 94% of the richest group have basic improved water services compared to just 15% of the poorest. Improved water, in this context, is defined by the World Health Organization/United Nations Children's Fund Joint Monitoring Program (JMP) as a piped water connection, tube well or borehole, protected dug well, protected spring or rainwater collection . A similar trend in Paraguay is illustrated in Figure 1.1, where 79% or the richest population of the country have access to improved and uncontaminated water, while only 37% of the poorest population have the same access. In rural communities, this gap shifts to 67% and 27% respectively, whereas in urban areas there is more access at 80% and 53% respectively (UNICEF/WHO, 2019).

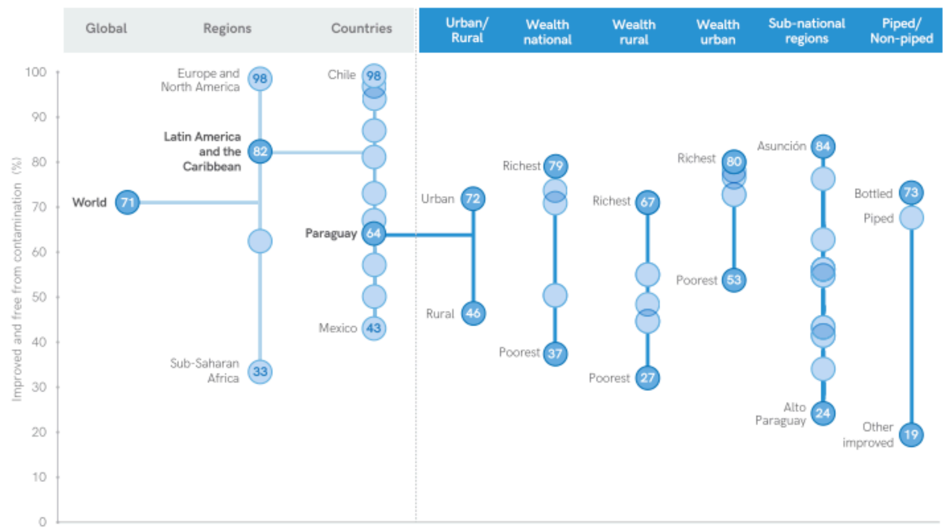

Figure 1.1. Inequalities in drinking water access and quality presented from the global, regional and country context, and further focusing on sub-populations of Paraguay in 2016 (UNICEF/WHO, 2019).

In an effort to bridge the gaps that these geographic and wealth disparities impart on water access, current water disinfection technologies have focused primarily on low-cost, point-of-use (POU), household water treatment (HWT) solutions including chlorination, filtration, boiling, flocculation/disinfection and solar water disinfection (SODIS) (Clasen et al. 2007; Sobsey et al. 2008; McGuigan et al. 2012). It is also a popular practice for homes to receive treated water by truck delivery (Sikder et al., 2020). Unfortunately, POU HWT places a burden on individuals to change their daily habits, and post-study compliance rates are often low (Sobsey et al., 2008). Community-scale systems are often perceived to save time and be less burdensome than HWT options (Cherunya et al., 2015), but they still need to be low-cost, easy to use, and sustainable (McGuigan et al., 2012), and require a dedicated person to maintain them.

In this work, direct and indirect uses of ambient solar UV radiation for water disinfection are examined at the community-scale and compared with traditional water disinfection methods. “Direct” UV treatment systems will be those that utilize ambient UV radiation directly to inactivate waterborne pathogens, while “indirect” applications will use the ambient solar radiation to power commercial UV reactors for this same purpose, generally by using ambient solar radiation to generate electrical power, which in turn is then used to power a small, commercial UV disinfection system.

The trend of increasing ambient solar spectral irradiance, including UVB, as a function of decreasing latitude (Frederick et al., 1989) suggests that countries at tropical latitudes, which are some of the most affected by lack of access to safe water, are some of the best suited to utilize solar water disinfection applications (Nalwanga et al., 2014). These areas are also disproportionately affected by poverty (Sachs et al., 2001). SODIS is often used as a process for water treatment in these locations due to UV availability, affordability of the technology, and low operational cost (McGuigan et al., 2012). Therefore, improving current practices for using ambient UV radiation for water disinfection can improve water quality access for those who are least likely to have access.

Traditional SODIS methods involve the use of transparent plastic bottles (McGuigan et al., 1998) or transparent plastic bags (Gutiérrez-Alfaro et al., 2017; Lawrie et al., 2015) as containers to expose water to direct, ambient solar radiation. These exposure scenarios result in increases of water temperature and formation of reactive oxygen species within the container, resulting in inactivation of microbial pathogens (Luzi et al., 2016). Common plastic containers that are used for these applications are often made from polyethylene terephthalate (PET), which is effectively opaque to UVB radiation. Plastic that is transparent to at least a portion of the ambient UVB spectrum allows the additional inactivation mechanism of DNA damage into the SODIS process (Busse et al., 2019; Fisher et al., 2008). Enhancement technologies that aim to improve SODIS disinfection performance and decrease time of disinfection include solar reflectors (Kehoe et al., 2001; Mani et al., 2006; Wegelin et al., 2001), chemical additives (Fisher et al., 2012; Harding and Schwab, 2012), photocatalysis (Malato et al., 2009), solar mirrors (Kehoe et al., 2001; Rijal and Fujioka, 2001), and continuous-flow reactors (L. W. Gill and Price, 2010; Mbonimpa et al., 2012).

The performance of SODIS systems is influenced by multiple parameters including the amount of received UV radiation, container characteristics, and water quality parameters such as temperature, water turbidity, and the specific pathogens present (Acra et al., 1984). Most SODIS systems though, do not regulate their effluent water based on these parameters; instead, systems are operated using a given time of exposure based on sunny (6 hrs) or cloudy (2 days) conditions (Luzi et al., 2016). Improvements to the plastic SODIS bottles that improve performance characteristics (i.e., reflective and strongly absorbing [i.e., black] surfaces) also increase the cost of the technology, which is then compounded by the need to replace these bottles every six months (Sandec, 2002), creating an additional burden on individual users.

More complex methods to enhance performance of the SODIS process (i.e., solar reflectors, chemical additives, flow reactors) have been shown to fall short of providing safe drinking water, also due to lack of control over how much inactivation is actually taking place within the system as a result of variability in available sunlight. Specifically, in field testing of a household, batch process compound parabolic collector (CPC) with a concentration factor[1] of one (which was designed to distribute a homogenous spread of the UVA spectrum on the absorber tube), 5 hours of exposure to strong sunlight delivered the prescribed cumulative dose of UV radiation, but around 10^2 CFU/mL of *E. coli* remained in samples (Ubomba-Jaswa et al., 2009). Enhancement technologies are also not considered financially feasible water treatment options unless they are scaled to the community level (McGuigan et al., 2012), and the same can be extrapolated for indirect UV treatment technologies.

An alternative approach involves collection of ambient solar radiation, in a wider range (between 400 – 700 nm) than what can be used for direct methods of inactivation, by solar panels to power commercial UV water treatment reactors (Gold et al., 2012), utilizing the ambient radiation indirectly to achieve microbial pathogen inactivation. In this work, indirect UV technologies are hypothesized to provide more consistent effluent water quality as a result of the consistent and known output of lamps and therefore inactivation characteristics within the commercial UV reactors. It is also hypothesized that indirect applications of UV for water disinfection will be more feasible than direct applications for community water treatment, due to their capacity, reliability, and ease of use.

Decisions about appropriate water treatment interventions should also be informed by factors such as local conditions, user preferences, and system cost recovery (Clasen et al., 2007). Some previous studies have been limited in that they have not assessed, they have only described, behavioral factors influencing system adoption (Parker Fiebelkorn et al., 2012a). We also hypothesize that user acceptance will be greater for UV treatment versus chlorination because the aesthetics (*i.e.*, taste and odor) of the water treated with UV will be relatively unchanged as compared to chlorine treatment, which can result in adverse tastes and smells (Crider et al., 2018a).

[1] Concentration factor is the ratio of irradiation received at the base of the CPC to the irradiation entering the CPC at the front aperture, calculated by taking the inverse of the sine of the half acceptance angle of the CPC.

This work aims to improve the definition of variables that influence decision making on the appropriate application of water disinfection technologies in the field, while elaborating on case-based outcomes of application to report critical factors influencing system usage and sustainability.

1.2 Specific Aims

The research involves three specific aims:

Aim 1: To evaluate UV disinfection technologies and their technical feasibly (potential capacity, cost, environmental impact).

Aim 2: To evaluate potential alternate applications of UV disinfection beyond drinking water treatment in low-income countries.

Aim 3: To define factors that will inform selection of the most appropriate disinfection technology and evaluate the user acceptance of the system through site-specific experience.

CHAPTER 2. AMBIENT UV QUANTIFICATION

2.1 Introduction

UVB radiation (280 – 315 nm) is crucial to many chemical and biological processes at earth's surface (Palancar and Toselli, 2004). Due to the biologically damaging capacity of UVB radiation, it has been used for solar water disinfection applications (Fisher et al., 2012; L.W. Gill and Price, 2010; Mbonimpa et al., 2012). Traditional SODIS calls for exposure of water in plastic bottles to direct sunlight for one full day (6 hours including noon hours) on days when it is mostly sunny or 2 days when it is 50% or more cloudy (Luzi et al., 2016). Similar operating parameters have been defined for systems that aim to amplify ambient solar radiation and speed up the solar disinfection process, such as compound parabolic collectors (CPCs) (Ubomba-Jaswa et al., 2010). Changing, site-specific parameters also influence the effectiveness of SODIS systems, requiring more work to be done to understand UV as a function of altitude, season and weather (Rainey and Harding, 2005). As a result, SODIS systems often cannot consistently provide effluent water that is safe for consumption. Prediction and monitoring of available, site-specific UV radiation can inform system design and allow for process controls for water quality verification of solar water disinfection systems, which are otherwise unmonitored. Indirect treatment systems also require knowledge of available UV and visible spectral irradiance to size solar panel and back up battery systems more effectively.

By quantifying the ambient solar UV with measurement and modeling technologies, it will be possible to quantify the differences between measured and modelled ambient UV and use this data to inform site specific modelling and design of treatment systems.

2.2 Methods

2.2.1 USDA UVB Monitoring Network

The United States Department of Agriculture (USDA) operates a UVB monitoring network (https://uvb.nrel.colostate.edu/UVB/index.jsf) in partnership with Colorado State University. Most of the monitoring sites are located in the United States. All of the instruments in the network are mounted 1.5 m above ground level, and data are processed on a central data server for consistency (Wang et al., 2008). Spectral irradiance measurements are collected by a Multi-Filter

Rotating Shadow-band Radiometer (MFRSR) in the UV range (300 nm, 305 nm, 311 nm, 317 nm, 325 nm, 332 nm, and 368 nm) from sunrise to sunset in W/m^2nm. The accuracy of measurements from this instrument are impacted by the aerosol optical depth (AOD), instrument alignment, and tilt and accuracy of the angular response as a result of the instrument shape. The error in measurements of optical depth alone can be almost 1% (Alexandrov et al., 2007). This error is compounded by additional factors, most significantly ozone, cloud cover and aerosols (Wang et al., 2008).

2.2.2 Tropospheric Ultraviolet Radiation Model

The Tropospheric Ultraviolet and Visible radiation model (TUV) (version 5.3.1) (https://www2.acom.ucar.edu/modeling/tropospheric-ultraviolet-and-visible-tuv-radiation-model) was used to simulate historical UV spectral irradiance measurements. With this model, UV spectral irradiance can be simulated at earth's surface by accounting for scattering and absorption of solar UV radiation due to atmospheric composition (Madronich et al., 2011). Inputs to the model include site-specific latitude, longitude, time-zone, surface elevation, and atmospheric parameters.

The NASA Giovanni system (https://giovanni.gsfc.nasa.gov/giovanni/) was used to collect atmospheric data for input into the TUV model. Aerosol optical depth was obtained from the from the MODIS-Terra satellite (MOD08_D3 v6) characterized as Aerosol Optical Depth 550 nm (Deep Blue, Land-Only). Cloud fraction was obtained from MODIS-Terra satellites as Cloud Fraction from Cloud Mask (count of lowest 2 clear sky confidence levels, cloudy & probably cloudy/total count): Mean of Daily Mean (MOD08_D3 v6). Average cloud fraction is determined for each day, and the "Mean of Daily Mean" refers to the average of these values across a specified range of days. Simulations were conducted with and without cloud fraction because the average daily cloud fraction did not account for real-time changes in available ambient UV. Ozone was obtained from the OMI satellite categorized as Ozone Total Column (DOAS) (OMDOAO3e v003); values are reported in Dobson Units (DU). Nitrogen Dioxide (NO_2) was obtained with the OMI satellite as NO_2 Total Column (30% Cloud Screened v003) (OMNO2d v003); values are reported in $1/cm^2$ and converted to DU. Sulfur dioxide (SO_2) was obtained from OMI satellites as the SO_2 Column Amount (Planetary Boundary Layer) OMSO2e v003; values are reported in DU. Data for ozone, NO_2 and SO_2 were single values averaged across an entire day at a 0.25° spatial resolution.

The built-in function defin1 was used as a starting point for calculations because it was designed for calculations of spectral irradiance at the Earth's surface. This function uses a 2-stream delta-Eddington code to approximate the reflection and transmission of diffuse radiation in an atmospheric layer. Output values are the sum of direct and diffuse radiation. It also provided weighted irradiances of UVB (280 – 315 nm), UVB* (280 – 320 nm), and UVA (315 – 400 nm). When values were not available from the NASA Giovanni system, the default TUV parameters were used. Default parameters in this input file for the NASA inputs described above were: ozone = 300 DU, NO_2 = 0, SO_2 = 0, aerosols = 0.235, cloud fraction = 0. Spectral data was output hourly for wavelengths between 280 – 730 nm in 1 nm increments.

2.2.3 Solar Light Datalogging Radiometer

A Solar Light datalogging radiometer (PMA2100) was set up with a PMA2106 sensor for non-weighted UVB detection between 0.001 – 20 mW/cm^2, and a PMA2107 sensor for non-weighted UVA and UVB detection between 0.001 – 200 mW/cm^2. The angular response of the sensors is cosine corrected. The radiometer was used to collect data in West Lafayette, IN (40.43 ^{o}N, 86.90 ^{o}W) for comparison to the UVB monitoring network and TUV. It was also used to collect data while conducting field work in Eldoret, Kenya (3.74 ^{o}N, 34.78 ^{o}E).

2.2.4 Data Analysis

Data available for each site were compared using basic error analysis at each wavelength (Equation 2.1). The absolute value of the numerator term was not taken so that the result would indicate over- and under-prediction or measurement.

$$\% \, error = \frac{simulation - measurement}{measurement} \, x \, 100$$ Equation 2.1

2.3 Results

The error between USDA measurements and TUV simulations from West Lafayette, IN on a mid-summer day are presented in Table 2.1.

Table 2.1. Summary of percent error between USDA UVB Monitoring Network measurements and TUV estimates for West Lafayette, IN on July 10, 2016 during clear conditions and when cloud cover was modeled (Busse et al., 2019).

(nm)	Modeled Clouds (N = no; Y = yes)	Time (hh:mm) 9:00	10:00	11:00	12:00	13:00	14:00	15:00
300	**N**	-12.28	-17.11	-16.73	-20.27	-15.06	4.57	-14.87
	Y	-16.74	-21.62	-20.95	-24.4	-18.96	1.27	-19.07
305	**N**	8.57	5.19	5.1	3.22	7.35	21.32	7.81
	Y	5.24	2.02	2.23	0.5	4.81	19.1	4.95
311	**N**	11.68	9.68	9.73	8.59	12.33	26.59	13.36
	Y	8.58	6.86	7.28	6.31	10.24	24.75	10.99
325	**N**	-14.99	-16.07	-15.19	-16.15	-11.45	6.88	-10.79
	Y	-18.94	-19.46	-18.04	-18.72	-13.82	4.78	-13.64

*Negative values indicate under-prediction of the TUV model in comparison to the USDA measured values

This analysis indicates that TUV both over- and under-predicts the amount of available UV radiation, in some instance by over 20%, and not in a consistent or predictable manner. Therefore, it is important to measure the amount of ambient UV for solar disinfection applications to ensure the effluent water from these systems has been appropriately disinfected. In locations where the USDA monitoring network does not extend, portable meters, such as the PMA2100, can be used to measure ambient UVA and UVB.

Data were collected with the PMA2100 for Eldoret, Kenya (46 days) and West Lafayette, IN (11 days). In both locations, cloud cover appeared to be a significant contributor to decreases in available UV radiation. Figure 2.1 illustrates points in the UVA+UVB and UVB spectra where visually cloudy skies resulted in drops in the available amount of ambient UV radiation at Earth's surface in Eldoret, Kenya.

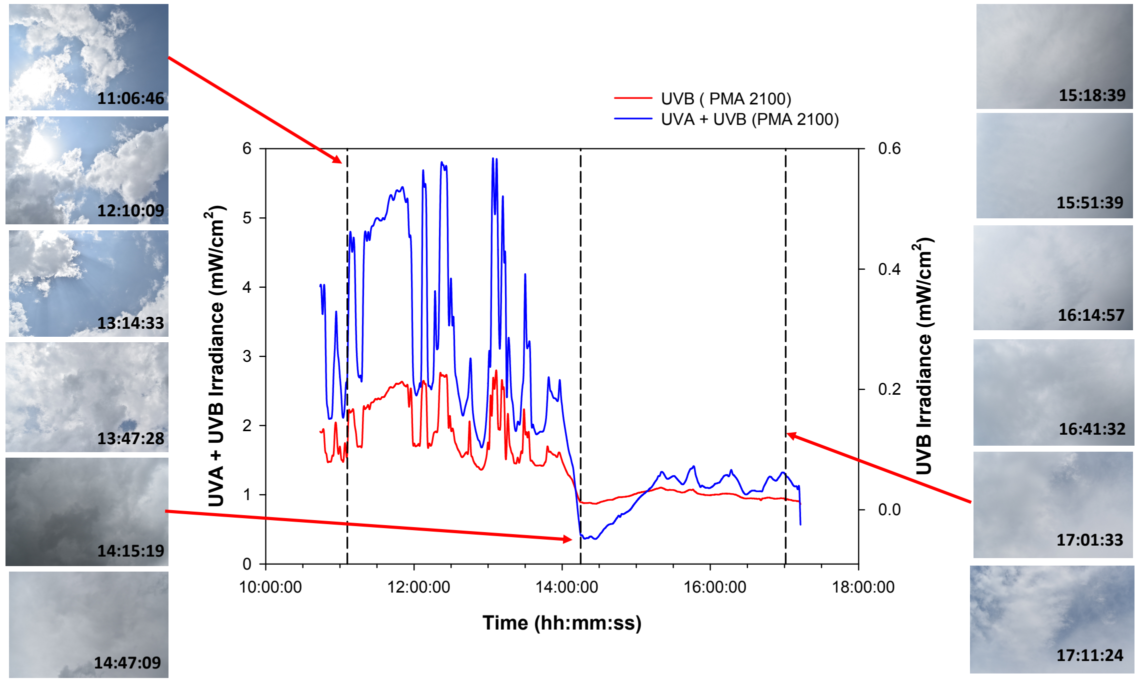

Figure 2.1. Visual tracking of the influence of cloud cover on amount of combined UVA/UVB (—) and only UVB (—) measured with the PMA2100 instrument in Eldoret, Kenya on July 30, 2017. The pictures, which were taken at a position near the monitor, are labelled with the local time at which they were taken. The vertical dashed lines represent times on the plot that correlate with 11:06:46 AM, 14:15:19 PM, and 17:01:33 PM from left to right. The red arrows indicate the pictures of the sky that correlate with these times.

The decrease in available UVA/UVB and UVB from 11:06:46 AM to 14:15:19 PM, associated with the visual increase in cloud cover, is consistent with previous studies indicating that cloud cover is one of the most influential factors affecting surface UV (Buntoung and Webb, 2010). These initial findings support the need to account for cloud cover in numerical simulations of ambient solar UV radiation, though existing models have been unable to account for the full extent of UV variability caused by cloud cover (Grant and Heisler, 2000). In this work specifically, cloud cover data from the NASA Giovanni system was applied; however, these data are only available as an average value for an entire day, so trends in the real-time influence of cloud cover cannot be modelled.

2.4 Conclusion

From this work, TUV simulations were used as input to ray tracing models in sections 3.2.2 and 8.2. TUV and the USDA monitoring network data were used to estimate the amount of radiation available for field studies (section 3.2.5).

Future work can further compare the measurements from portable devices to those of the USDA monitoring network to determine whether they measure ambient UV at high enough accuracy to be used for calculating UV dose for solar disinfection devices in the field, and to use this information for designing process controls for solar UV disinfection applications.

CHAPTER 3. COMPOUND PARABOLIC COLLECTOR DESIGN

3.1 Introduction

CPCs have been designed for water disinfection applications to enhance solar disinfection through amplification of ambient radiation (Gómez-Couso et al., 2012; Mbonimpa et al., 2012; Nalwanga et al., 2014), but they are often limited by their lack of process controls, much in the same way that traditional SODIS is limited. Ambient solar UV spectral irradiance changes significantly in real-time, as seen in Figure 2.1, and disinfection efficacy is directly linked to the amount of radiation being received by the contaminated water.

Further, CPCs have not traditionally produced enough water to be applied at the community scale. (Ubomba-Jaswa et al., 2010) demonstrated that a batch CPC was able to yield viable *E. coli* concentration below the limit of detection after 5 hours of exposure to sunny conditions (Plataforma Solar de Almería, Spain), but it only produced 25 L of water at a time. (Mbonimpa et al., 2012) then demonstrated that a continuous-flow CPC achieved between 0.5-3.5 $\log_{10}$-units of inactivation of *E. coli* between 11 AM and 4 PM at a flow rate of 9 mL/min (West Lafayette, IN). The goal of this work was to optimize the existing CPC system from (Mbonimpa et al., 2012) to increase flow-rate and better understand if community-scale capacity can be achieved to warrant further development of process controls.

3.2 Methods

3.2.1 CPC Design Parameters

The cross-section of the CPC for this study was developed based on the approach of (Mbonimpa et al., 2012) using equationsEquation 3.1 and Equation 3.2. to define one half of the cross-section, where X = 45 cm, Y = 21 cm, and f = 2.3 cm. The other half of the cross-section was defined by symmetry about a vertical line through the origin.

$$X = \frac{2f * \cos(\theta)}{(1 - \cos(\theta))} \quad \text{Equation 3.1}$$

$$Y = \frac{2f * \sin(\theta)}{(1 - \cos(\theta))}$$ Equation 3.2

(X,Y) = Cartesian coordinates of the CPC profile

θ = angle between the line joining the focus, point on the parabola and x-axis

f = focus of the parabola.

The half acceptance angle of this CPC was 7.5°, which was used to calculate the maximum concentration ratio (C_{max}), the ratio of the input and output aperture area calculated by equation Equation 3.3, of the CPC (Prapas et al., 1987).

$$C_{max} = \frac{1}{\sin(\theta_c)}$$ Equation 3.3

Where,

C_{max} = is the maximum concentration ratio

θ_c = half acceptance angle (radians).

C_{max} of this CPC was 7.66, implying that the ambient solar spectral irradiance can be amplified by this factor given perfect specular reflection of the CPC surfaces at all wavelengths. A CPC device based on this cross-sectional geometry was operated as a continuous-flow reactor by positioning a UV-transparent tube at the focus of the CPC cross-section. Water was pumped through the system at a volumetric flow rate of 9 mL/min. A goal of this work was to increase throughput of the system, relative to static SODIS systems, by optimizing the half-acceptance angle (θ_c) of the CPC while incorporating minimal solar tracking.

3.2.2 Ray Tracing Simulations

A ray tracing software package (Photopia V 2017.3.0.8450, LTI Optics, Westminster, CO) was used to simulate amplification of ambient solar spectral irradiance within the CPC. Photopia is a raytracing software package developed for photometric analysis of optical systems. Users are able to design a 3-dimensional system and assign objects within the computational domain with reflective, refractive and transmissive properties to allow for photometric analysis within the CAD based interface (Yu et al., 2014). Modeling with Photopia has been applied previously to study solar energy collection in CPC reactors (Su et al., 2012), and it was used in this study with a sunlight model and input from TUV simulations to model the concentration of ambient solar radiation at given points within the altered CPC design. The Photopia model of the CPC is illustrated in Figure 3.1a.

The CPC was constructed and simulated with an aluminum foil reflective inner surface, and a borosilicate glass tube to transport water along the bottom of the reactor. The glass tube had a 5 cm outer diameter, 5 mm wall thickness and 125 cm length. The model materials (refractive indexes for water and borosilicate glass, and absorption coefficient for water) were modified for each wavelength studied.

Small, transparent receptor spheres were included in the model to calculate local fluence rate at several cross-sectional locations within the transmission tube (Figure 3.1c). Small spherical receptors were chosen to match the formal definition of fluence rate: radiant power per unit area imposed on an infinitesimally-small sphere (IUPAC, 1997). The centroids of the receptor spheres were placed at five locations throughout the cross-section of the transmission tube (Figure 3.1b).

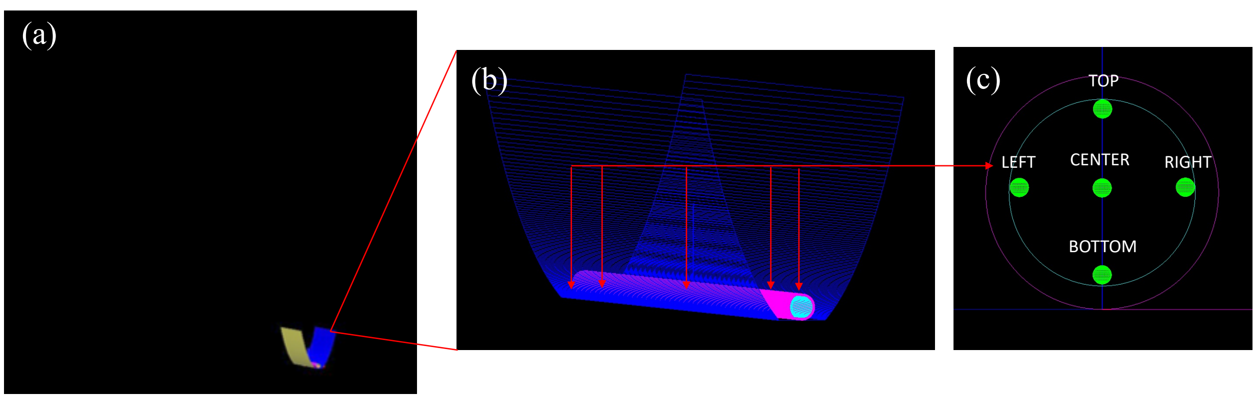

Figure 3.1. CPC setup in Photopia (a) the overall reactor, (b) the location of the borosilicate glass transmission tube within the CPC cross-section and (c) a cross-section of the transmission tube showing the receptor particles at each location.

To model ambient solar radiation, a "numerical lamp" was selected as a planar source at a size that would illuminate the entire surface of the CPC, with an output equal to ambient solar irradiance. The solar zenith angle for the day of this simulation (August 1) in West Lafayette, IN at noon was determined with the TUV data set and used as the lamp angle in the model. This was verified by the USDA UVB monitoring network, which indicated a solar zenith angle of 22.72°, equating to a 67.28° angle above horizontal for the sun lamp. Established sun lamp models with pre-defined solar zenith angles are available at 10° intervals in Photopia, so a sun lamp at 70° was used in this study. Output from the TUV model for West Lafayette, IN at 300.5 nm, 305 nm, 311 nm and 325 nm was scaled by the acceptance area of the CPC and an integration of a 10 nm wavelength range. This output was used as an input to Photopia in radiant watts.

3.2.3 CPC Design

The results of simulations of the original CPC (θ_c = 7.5°), angled toward the sun, indicated that within the water transmission tube at the bottom of the CPC, C_{max} only reached around 0.55 at the best performing location (bottom of the tube). This was less than 1, the C_{max} of a flat plate, because the CPC did not direct radiation to the bottom center of the CPC where the transmission tube was located (Busse, 2016). Therefore, the half-acceptance angle was reduced to around 6.5 degrees, subsequently increasing the angular extent of the walls from 59.4° to 70°. This resulted in a CPC with much higher walls, that directed radiation more towards the location of the transmission tube within the CPC. This change also increased the theoretical maximum concentration ratio of the CPC to 8.83, but to save construction costs, the design was truncated by 50%, reducing the theoretical concentration ratio by 10% to 7.95 (Yu et al., 2014). The truncated CPC modeled in Photopia provided a maximum concentration ratio of between 5.2 – 5.37 at the bottom of the transmission tube at the center three positions (Figure 3.1b).

3.2.4 Construction

The optimized CPC was constructed using Paulownia lumber because of its low density and dimensional stability. All wood was surfaced using both a planer and jointer to allow for construction of a predictable and consistent optical surface. A jig was built to make identical spines (forms) for the 8 ft stretch of CPC. Spines were placed at 2' (60 cm) intervals to align the strips that defined the CPC cross-sectional shape (

Figure 3.2a). 1" wide x ¼" thick strips of lumber were used to line the inside of the CPC (

Figure 3.2b). Aluminum foil was attached to poster boards with spray adhesive to create a smooth, low-cost aluminum surface, and to also allow for durability of the aluminum foil during testing (

Figure 3.2c).

Figure 3.2. CPC construction process; (a) CPC skeleton with spines placed every 2 ft along the 8 ft section; (b) addition of the 1 in wide wood strips to create a curved inner CPC surface; (c) addition of aluminum foil for reflection and concentration of ambient solar irradiance within the CPC.

3.2.5 Field Testing

Field testing of the CPC was conducted on the 2nd story roof of Hampton Hall on Purdue University's campus on September 19, 2016. The PMA2100 solar UVB monitor was used to measure integrated amount of UVB and UVA+UVB throughout the experiment.

An aqueous suspension of *S. typhimurium* LT2 (10^6 cfu/mL) and *E. coli* (10^6 cfu/mL) in Minimal Salts Medium (MSM) was prepared. The sterile MSM consisted of 0.68 g/L KH_2PO_4, 2.2 g/L K_2HPO_4 $3H_2O$, 0.1 g/L $MgSO_4$, and 1.0 g/L NH_4NO_3 in deionized (DI) water at a pH = 7.

Salmonella typhimurium LT2

Frozen cultures of *S. typhimurium* LT2 were stored in a 1:1 ratio sample:glycerol at -80°C. A sample of *S. typhimurium* LT2 (TL155) was removed from the freezer and thawed. The *S. typhimurium* LT2 culture was maintained and washed with sterile lysogeny broth (LB) consisting of 10 g/L tryptone, 5 g/L yeast extract and 10 g/L sodium chloride in RO water. For washing, the thawed cells were centrifuged for 8 minutes at 7500 x g in an Eppendorf tube. Supernatant was removed and the pellet was re-suspended in 1 mL of LB and centrifuged. The wash step was repeated an additional time to fully remove any residual glycerol from the freezing medium. After the last wash step, the LB was removed while the pellet was re-suspended in LB and transferred to a sterile flask containing 100 mL autoclaved LB solution. This starter culture was incubated overnight at 37°C while being stirred with a magnetic stir bar and plate, or on a shaker. After incubation, 1 mL of the culture was transferred to a new autoclaved flask of 100 mL LB to inoculate a subculture. Once the subculture reached an optical density of 1.0, 10 mL of sample was removed, centrifuged and re-suspended in 16 L MSM. This approach yielded a subculture concentration (N_0) of approximately 10^6 cfu/mL.

Escherichia coli

Frozen cultures of *E. coli* were stored in a 1:1 ratio sample:glycerol at -80ºC. A sample of *E. coli* was removed from the freezer and thawed. The *E. coli* culture was maintained and washed with sterile nutrient broth (NB) in RO water (8 g/L). For washing, the thawed cells were centrifuged for 8 minutes at 7500 x g in an Eppendorf tube. Supernatant was removed and the pellet was re-suspended in 1 mL of NB and centrifuged. The wash step was repeated an additional time to fully remove any residual glycerol from the freezing medium. After the last wash step, the NB was removed while the pellet was re-suspended in NB and transferred to a sterile flask containing 100 mL autoclaved NB solution. This starter culture was incubated overnight at 37°C while being stirred with a magnetic stir bar and plate, or on a shaker. After incubation, 1 mL of the culture was transferred to a new autoclaved flask of 100 mL NB to inoculate a subculture. Once the subculture reached an optical density of 1.0, 10 mL of sample was removed, centrifuged and re-suspended in 16 L MSM. This approach yielded a subculture concentration (N_0) of approximately 10^6 cfu/mL.

Experimental setup

Based on the concentration ratio determined through ray tracing modelling of the CPC, the predicted amount of available radiation in West Lafayette in September, and the inactivation kinetics of *S. typhimurium* LT2, a flow rate of 15 mL/min was calculated to ensure at least 2-$\log_{10}$ units of inactivation within the reactor. The tilt angle was set to 27º to match the expected zenith angle of the sun on a September day at the given location (

Figure 3.3).

(a)

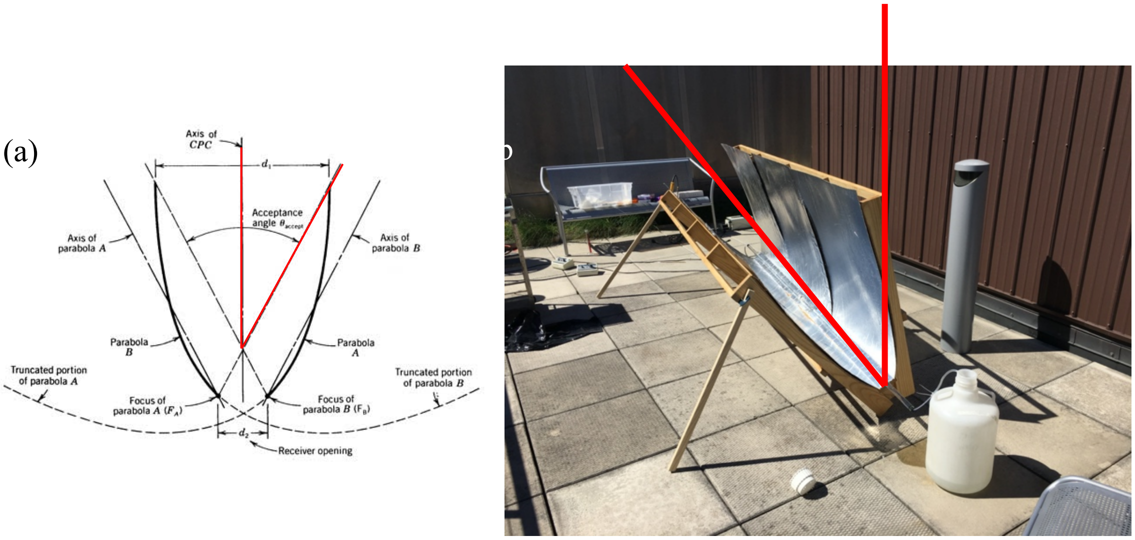

Figure 3.3. a) Half acceptance angle of a CPC (Stine and Geyer, 2001) and b) the resulting tilt angle of the CPC on the roof of Hampton Hall, where the axis of the CPC is directed at the sun's elevation angle.

The CPC was covered with black fabric to prevent UV disinfection while the system was filled with the DI water and purged of as much air as possible using a peristaltic pump. The microbial suspension was then added at the inlet, the CPC was uncovered, and the suspension was pumped through the system until the target residence time was reached, at which point, sampling began. Residence time was determined to be approximately 45 minutes based on the volume of the transmission tube divided by the steady-state flow rate through the reactor. Samples were collected every 30 minutes at the inlet and outlet of the reactor. Samples were serially diluted 5 times and plated in triplicate. Plates were incubated for 24-48 hours at 37^oC. Plates were counted and log_{10}-units of inactivation were determined.

3.3 Results

The inactivation responses of *E. coli* and *S. typhimurium* LT2 within the reactor during the experiment are illustrated in Figure 3.4, where between 3-log_{10} to 5-log_{10} units of inactivation of *E. coli* were achieved at a 15 mL/min flow rate. *S. typhimurium* LT2 under the same set of conditions was at least 4-log_{10} units of inactivation at all sample times. The CPC studied by (Mbonimpa et al., 2012) operated at a flow rate of 9 mL/min, and it only achieved between 0.5-

log_{10} to 3.5-log_{10} units of inactivation of *E. coli.* In this study there was about 65% of the maximum UVB radiation at 300 nm than that in the work of (Mbonimpa et al., 2012), which were 0.0059 W/m^{2}nm and approximately 0.009 W/m^{2}nm respectively, as reported by the USDA UVB monitoring network at the Purdue Agronomy farm.

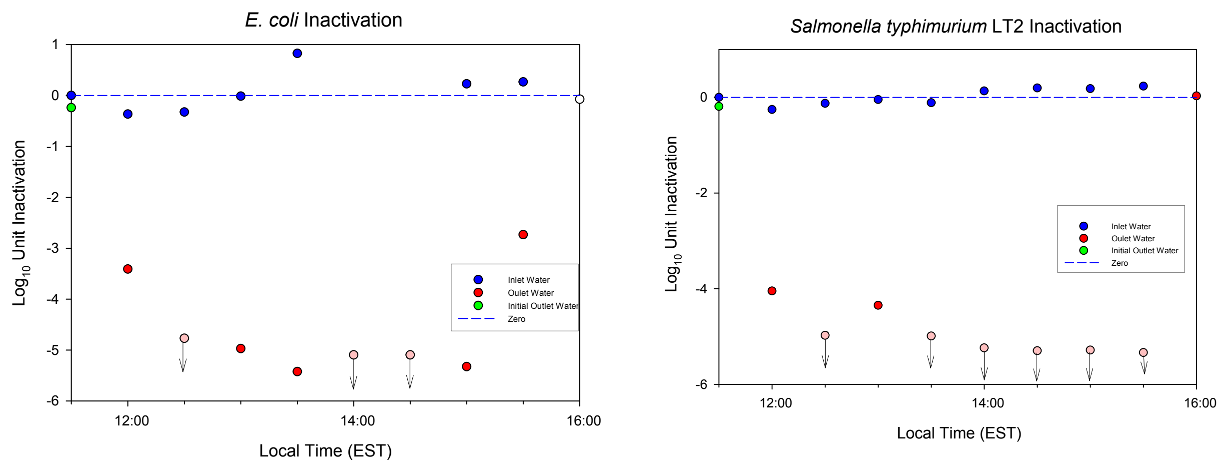

Figure 3.4. Bacterial inactivation as a result of sun exposure in the CPC on September 19, 2016 at a flow rate of 15 mL/min. Lighter red dots with a downward arrow represent inactivation calculations where the amount of bacteria was <1 countable colony.

3.4 Conclusion

These results indicate an improvement of the tilt angle of the CPC and amplification ratio within the CPC, relative to previous work. This allowed an increase of the water flow rate through the system, while also improving microbial inactivation. This design was used in the following Life Cycle Assessment.

CHAPTER 4. Evaluation of indirect technologies

4.1 Introduction

With the variable reliability of SODIS and enhanced SODIS systems, it is relevant to compare their behavior with commercial UV water disinfection reactors powered by solar panels. Two commercially available reactors were evaluated in this work for their performance in inactivating *S. typhimurium* LT2. NSF International and the American National Standards Institute (ANSI) developed a standard to define classes for point-of-use and point-of-entry (POU and POE, respectively) UV disinfection systems (NSF/ANSI 55) based on their performance capabilities. Class A systems are designed to inactivate microorganisms, including bacteria, viruses, and protozoan parasites, in well or surface waters. Class A systems require a nominal UV_{254} dose of 40 mJ/cm^2. Class B systems are designed to reduce non-pathogenic bacteria within the system at a nominal UV_{254} dose of 16 mJ/cm^2.

4.1.1 LP Reactor

Two small-scale commercial devices were evaluated in this study. The first was a Viqua VT1 reactor, which utilizes a low-pressure (LP) Hg lamp, with monochromatic output at nominally 254 nm. The manufacturer provided data to indicate nominal UV dose delivery as a function of flow rate for this reactor. Based on these data, the company's standard for UV_{254} dose is 30 mJ/cm^2 corresponded to an operating flow rate of 1 GPM through the reactor. A UV_{254} dose of 40 mJ/cm^2 has been reported to be delivered by this system at a flow rate of 0.7 GPM (VIQUA, n.d.), meeting NSF/ANSI 55 standards. The system requires greater than 75% UV transmittance, but flow rates that meet the standards provided are based on 95% UV transmittance. The system also requires that influent water have <0.3 mg/L iron, <7 gpg hardness, <1 NTU turbidity, <0.05 mg/L manganese and < 0.1 mg/L tannins.

4.1.2 LED Reactor

The LED reactor used in this study was an early model from Aquisense, which was not assigned a model number; the system was built around UV light emitting diodes (UV LEDs) that had peak emission at approximately 280 nm. The maximum volumetric flow rating for this system was 2 gpm (7.6 L/min), corresponding to a nominal UV_{280} dose of up to 80 mJ/cm^2 when the UVT_{280} is greater than 90%. No further parameters of the system were available in the provided operating manual.

4.2 Methods

The experimental setup for full-scale reactor testing is illustrated in Figure 4.1. Tank 1 (left tank in Figure 4.1) was filled with DI water while the right tank, tank 2, was filled with a bacterial suspension of *S. typhimurium* LT2. A valve separated the inlets between the two tanks, allowing for the ability to switch between tanks before the pump. The reactor, after the pump, was interchangeable.

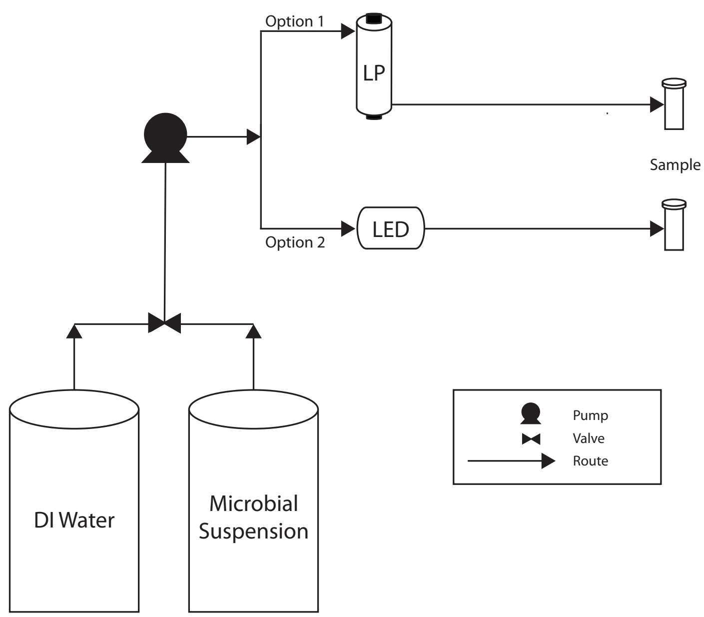

Figure 4.1. Flow schematic of the experimental setup for indirect reactor testing. Tank 1 contained DI water and Tank 2 contained the bacterial suspension. The pump pulled water from the designated tank through the reactor.

Before sampling for each set of transmittance conditions, the system was rinsed with chlorinated water, then DI water, and then brought to steady-state concentration with the bacterial suspension in preparation for inactivation of *S. typhimurium* LT2. Once the system reached a steady-state concentration, a sample was taken from the outlet of the system with the lamp off to determine the initial concentration of viable bacteria in the system (N_0), and then the UV lamp was turned on and allowed to warm up. Samples were collected in triplicate (N) at the outlet for a series of flow rates (0.53 gpm, 0.71 gpm, 1.12 gpm, , 1.49 gmp, and 1.72 gpm). Once complete, the transmittance of the bacterial suspension was adjusted using sodium thiosulfate, and the experiment was conducted again through the same set of flow rates.

4.3 Results

For the LP reactor, transmittance conditions of 99%, 95% and 85% at 254 nm were examined. For the LED reactor, transmittance conditions of 95%, 89% and 79% at 280 nm were examined. ●Figure 4.2 illustrates the resulting inactivation of *S. typhimurium* LT2 within both reactors with increasing flow rate through the reactor from 0.53 gpm to 1.72 gpm. The LP reactor consistently achieved greater than 3 $\log_{10}$-units reduction whereas the LED reactor never achieved more than around 2 $\log_{10}$-units reduction.

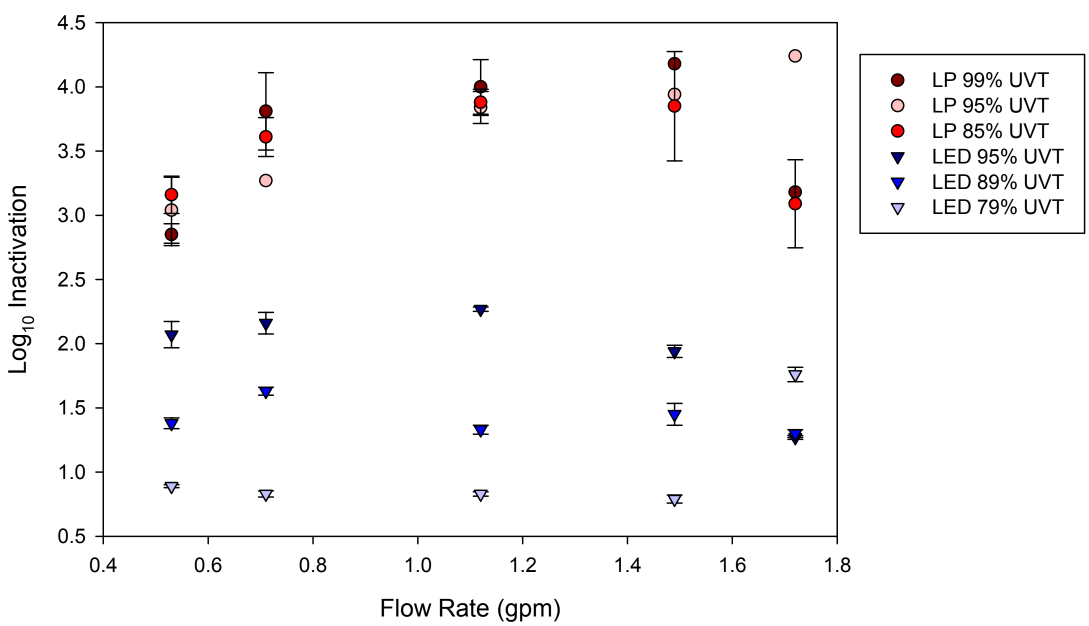

Figure 4.2. Inactivation of *S. typhimurium* LT2 as a function of flow rate through both the LP and LED UV reactors. The three data sets represented by red circles illustrates the inactivation within the LP reactor under varying transmittance conditions (●99% UVT, ● 95% UVT, ○ 85% UVT), and the set of blue triangles illustrates inactivation within the LED reactor under varying transmittance conditions (▼ 95% UVT, ▼ 89% UVT, ▽ 79% UVT).

4.4 Conclusion

It was expected that with increasing flow rate through the reactor, there would be a decrease in inactivation, but the results for the LP reactor show an increase in inactivation with increased flow rate up to 1-1.5 gpm after which point inactivation decreases. One explanation for this result could be that the flow through the reactor is in the transitional flow regime for the first two flow rates (approximately Re = 2407 and Re = 3240 assuming the fluid within the reactor has the same flow properties as water and using the internal reactor diameter as the characteristic length scale), which introduces high energy and intermittent puffs into the flow (Trip et al., 2012), and this could lead to inconsistent flow patterns within the reactor. The reactor was also mounted vertically for these experiments, which could introduce a different flow pattern within the reactor than when it is in the horizontal orientation. Future studies should be conducted to investigate this phenomenon, but this is outside the scope of this work.

From this analysis, the LP reactor was demonstrated to be the most reliable for inactivation of *S. typhimurium* LT2, and therefore, the most trustworthy option for implementation in water treatment systems for future studies. As a note, newer LED-based reactors have been shown to be more effective than the early model tested in this study.

CHAPTER 5. COMPARATIVE LIFE CYCLE ASSESSMENT OF WATER DISINFECTION PROCESSES FOR APPLICATION IN DEVELOPING COUNTRIES

5.1 Abstract

In July 2010, the UN General Assembly recognized the universal human right to sufficient water for health and sanitation (United Nations, 2010). The reliable disinfection of water plays a critical role in public health, as do the environmental impact and sustainability of the water disinfection methods. This study presents an investigation of the life cycle impacts of four ultraviolet disinfection systems utilizing ambient solar radiation directly and indirectly for water disinfection in developing countries. Two traditional treatment practices in these settings, chlorination and water delivery, were evaluated for comparison. Existing literature was used to define a life cycle functional unit for each system, which allowed quantification of material use, infrastructure requirements, and life cycle of the original components of each system and those needed to keep them operational for the studied lifespan. The impact of each system was simulated in the Life Cycle Analysis software SimaPro. Quantitative comparisons were developed related to the use of each technology at community (1000 LPD), school (500 LPD), small group (100 LPD), and family (30 LPD) scales. Life cycle analysis demonstrated that the choice of a disinfection technology is dependent on both system life expectancy and the production rate over this lifetime. For all studied cases, chlorine had the lowest impact in all impact categories, but end-user acceptance of chlorine in LDCs is low. Therefore, a potential alternative for long-term (10+ years), high production (500+ LPD) scenarios is disinfection based on low-pressure (LP) mercury lamps as the UV source, which had the next lowest normalized impact in the most impact categories. Considerations of end-of-life in LDCs highlights the compounding factors that influence selection of a technology beyond the material impact, such as waste disposal outside of the context represented in an LCA.

5.2 Introduction

More than 90% of the world's population now has access to an improved source of drinking water, compared to only 77% of the population of least developed countries (LDCs)

(WHO/UNICEF, 2015), where LDCs are defined by their income per capita, human assets, and economic vulnerability (United Nations Committee for Development Policy, 2020). An even lower percentage have access to safe drinking water, because the current definition of 'improved' does not account for the microbial safety of the water (UNICEF/WHO, 2011). The World Health Organization (WHO) estimates that roughly 826,000 deaths are caused every year by diarrheal diseases related to lack of safe water and sanitation (WHO, 2015). To understand how solutions can be developed, it is important to consider the patterns of wealth and poverty on a global scale. Nearly 40% of the world's population lives in tropical areas, yet only about 17.4% of the world's GNP is generated there. This is due, in large part, to the impacts of geography on the economy from prevalence of disease to the impact on agriculture, as well as the lasting effects of colonialism and neocolonial economic structures (Kothari, 2005; Sachs et al., 2001). Despite these challenges, the increase in available ambient solar radiation as a function of decreasing latitude (Frederick et al., 1989) suggests that countries at tropical latitudes are some of the best qualified to harness the power of the sun for solar water disinfection applications (Nalwanga et al., 2014), which might enable low-cost, sustainable solutions to the provision of safe water.

Small-scale water treatment systems in the United States rely heavily on disinfection, where over 50% of systems serving 500 people or less use only disinfection with no additional treatment (USEPA, 2011). Therefore, with decentralized, small-scale water treatment systems commonly employed to address contaminated water in LDCs (Fewtrell and Colford, 2005), the proper selection of disinfection technologies for low-resource settings is crucial in order to provide reliable water treatment.

In previous life-cycle analysis (LCA), ultraviolet (UV) irradiation has been shown to be more sustainable (considering environmental, health, and economic benefits) than chlorination in wastewater applications due to the need for de-chlorination of the effluent in this context (Das, 2002). Yet few LCAs have been conducted to analyze and compare the environmental and economic impacts of chlorination and ultraviolet disinfection for drinking water applications, and those that have been done were conducted for developed countries. In 2014, the US EPA published a complete life-cycle analysis of municipal-scale water disinfection technologies in the United States laying the groundwork for analysis of large-scale systems. They found that impacts were largely independent of disinfection method for large-scale systems, though traditional UV treatment was more impactful than chlorine by most metrics due to higher electricity use (Cashman et al., 2014). Energy consumption has frequently been identified as the cause for high environmental impact of water treatment technologies (Garfí et al., 2016; Lemos et al., 2013; Yan et al., 2018). This highlights the importance of broadly available solar energy for use in disinfection systems in LDCs. But important gaps remain in understanding point-of-use and small, community-scale systems. For small-scale water treatment systems, (Jones et al., 2018) found that replacing chlorine with UV treatment, using a conventional system based on low-pressure mercury (Hg) lamps as the UV source, was only valuable when there was a high pumping pressure in the system and when the water does not need to be filtered prior to disinfection. This work aims to build upon this understanding by providing a comparative LCA of several UV disinfection methods utilizing solar resources for drinking water disinfection in tropical, low-income areas. These processes are compared with conventional chlorination.

5.3 Methods

Life Cycle Analysis was conducted as described in the ISO14040 framework including end-of-life recycling rates for the United States (International Standard Organization, 2016). The functional unit of this analysis was defined as "1 cubic meter of water produced" by each system over a 1, 5, 10 and 20-year lifespan for each scenario (including replacement parts). Four reference flowrates were considered to evaluate community (1000 LPD), school (500 LPD), small group (100 LPD), and family (30 LPD) water production scales for each system.

5.3.1 Goal and Scope

System definition and system boundaries

Four UV disinfection systems, two using sunlight directly to disinfect water (direct systems) and two using sunlight to power a disinfection system (indirect systems), were considered in this study and were compared to traditional, widely-utilized methods of disinfecting water in developing countries (point-of-use chlorination) (Clasen et al., 2015) or attaining safe water (water delivery services) (Sikder et al., 2020; Whittington et al., 1990).

The UV systems were evaluated based on solar irradiance conditions in Kolkata, India, Santiago de Los Caballeros, Dominican Republic, and Nairobi, Kenya on the shortest day of the year for each respective location. The shortest day was chosen to represent the least amount of available ambient radiation, and thus the worst case, sunny-day operating conditions. This assessment across cities was designed to evaluate the effects of climate variations across the tropics, not provide a holistic assessment of water system rollout in each location; accordingly, LCA processes in EcoInvent were not localized.

Direct UV Technologies

Direct water disinfection technologies were defined as those that use the ambient solar UVB radiation to directly disinfect the water. For this simulation, both solar disinfection (SODIS) and a continuous-flow compound parabolic collector (CPC) represented direct applications of ambient solar UV for water disinfection.

SODIS

SODIS bags were evaluated instead of bottles in this study because they have been shown to increase disinfection performance as a result of the increased surface area for sun exposure (Gutiérrez-Alfaro et al., 2017; Sukkasi and Akamphon, 2013). Therefore, the bag shape was assumed to be a flattened ellipsoid for modelling purposes. SODIS bags are commonly made of polystyrene (PS) (Fisher et al., 2012; Gutiérrez-Alfaro et al., 2017; Lawrie et al., 2015), but polyethylene terephthalate (PET), polymethylmethacrylate (PMMA), and polypropylene (PP) are more suitable materials for SODIS applications due to their transmittance in the solar wavelength range and cost in comparison to durability when exposed to solar radiation (García-Gil et al., 2020). PET is opaque to UVB radiation (280-320 nm), but transmits UVA radiation (320-400 nm), whereas PMMA and PP transmit radiation in both the UVA and UVB ranges for direct pathogen disinfection within the SODIS reactor (García-Gil et al., 2020). Therefore, 1L, 4L, and 6L volumes were evaluated for a bag shape of each material (PET, PMMA, and PP). At each volume, the maximum depth of the modeled ellipsoid (and thus solar pathlength) remained constant.

SODIS bags were assumed to operate under standard conditions of 6 hours of direct exposure to ambient sunlight for disinfection on cloudless days and two days of exposure for days with greater than 50% cloud cover (Luzi et al., 2016). The NASA Giovanni system (https://giovanni.gsfc.nasa.gov/giovanni/) was used to obtain a daily average cloud fraction (MOD08_D3 v6.1) for 2019 in each of the three study locations. Days where the average daily cloud cover fraction was >0.5 were classified as cloudy. Kolkata, Santiago de Los Caballeros, and Nairobi had 197, 216 and 104 cloudy days, by this definition, respectively.

CPC

The CPC was designed based on equations from (Welford and Winston, 1978) with a half acceptance angle of 6.5° and truncated using methods from (Jadhav et al., 2013) to optimize CPC output in relation to the material required. The CPC used for prototype testing was constructed using Paulownia lumber (a stable lumber material that is readily available in many LDCs) lined with aluminum foil, and it utilized a borosilicate glass tube positioned at the CPC focal point for water transport (5 cm outer diameter and 5 mm wall thickness) (Mbonimpa et al., 2012). The flow rate within the reactor was set at 25 mL/min for a 2.4 m (8 ft) length. This was calculated based on the disinfection potential of *Salmonella typhimurium* LT2 at 310 nm (Busse et al., 2019), the ambient solar irradiance on a sunny day in July in West Lafayette, IN, USA as estimated by the Tropospheric Ultraviolet and Visible Radiation Model (TUV), and the amplification ratio within the reactor based on ray tracing simulations using Photopia (V 2017.3.0.8450, LTI Optics, Westminster, CO).

Indirect UV Technologies

Indirect water disinfection technologies were considered to be those that use solar panels to produce electrical current to charge batteries, which in turn are used to power a commercially available UV reactor for water disinfection. The two commercial UV reactors used in this analysis differed in reactor design and in lamp type, one relying on an LED system, while the other used a standard low-pressure (LP) mercury lamp. Both reactors were provided to the authors explicitly for the purposes of testing and were disassembled and reassembled for material inventory.

LP Lamp

The LP lamp reactor was designed to operate at 2 gpm (7.5 lpm) at 95% UV transmittance at 254 nm (UVT_{254}) to meet the United States public health standard of 16 mJ/cm^2 UV_{254} dose, with a 9000 hour useful lamp life. The system utilized a 9 W lamp and required 12 VDC for operation.

LED Reactor

The LED reactor was built around UV light emitting diodes (UV LEDs) that had peak emission at approximately 280 nm. The maximum volumetric flow rating for this system was 2 gpm, corresponding to a nominal UV dose of up to 80 mJ/cm^2 when the UVT_{280} is greater than 90%, with a useful lamp life of 4000 hours. The system utilized a 15 W lamp and required 12 VDC for operation.

Solar Panels and Batteries

The indirect reactors were assumed to be powered by a system of solar panels and lead-acid batteries. In all cases studied, one standard lead acid battery (45 Ah) was sufficient for the system to store enough power for operation without sunlight for one week. Solar panels were sized to be economically efficient (minimum cost per system) based on solar panel outputs and prices at Grainger Industrial Supply. The amount of radiation (300-700 nm) received by the panels on the shortest day of the year at each location was estimated using TUV. Inputs to TUV were determined for each location using the NASA Giovanni system for aerosol optical depth (MOD08_D3 v6.1), ozone (OMDOAO3e v003), nitrogen dioxide (NO_2) (OMNO2d v003), and sulfur dioxide (SO_2) (OMSO2e v003). When unavailable, TUV program default values were used. The efficiency of the solar panel models used varied between 6.4% and 13.1%. (https://www.grainger.com/product/SOLARTECH-POWER-Solar-Panel-26KH27).

Water Delivery

Water delivery is defined by the transport of treated water to individual households, where additional treatment of the water was not considered. The delivery vehicle for water was assumed to be a diesel-powered Lorry (tanker truck).

Chlorination

Point-of-use chlorination was modeled as the addition of chlorine to water in individual households. All chlorine was assumed to be standard household bleach; this was simulated as 5.25% sodium hypochlorite in water. The impact of purchasing bleach in 3.8 L, 1.9 L and 0.15 L volumes in standard high density polyethylene (HDPE) bottles with child resistant polyethylene (PE) caps (The Cary Company) was evaluated.

System Boundaries

Figure 5.1 provides the boundaries used for the LCA of each system, which were limited to the materials that directly made up each system and the required materials to maintain them for the studied time periods. Emissions to air, water, and solid wastes were implicit in each step and are thus were omitted from the visual system boundaries.

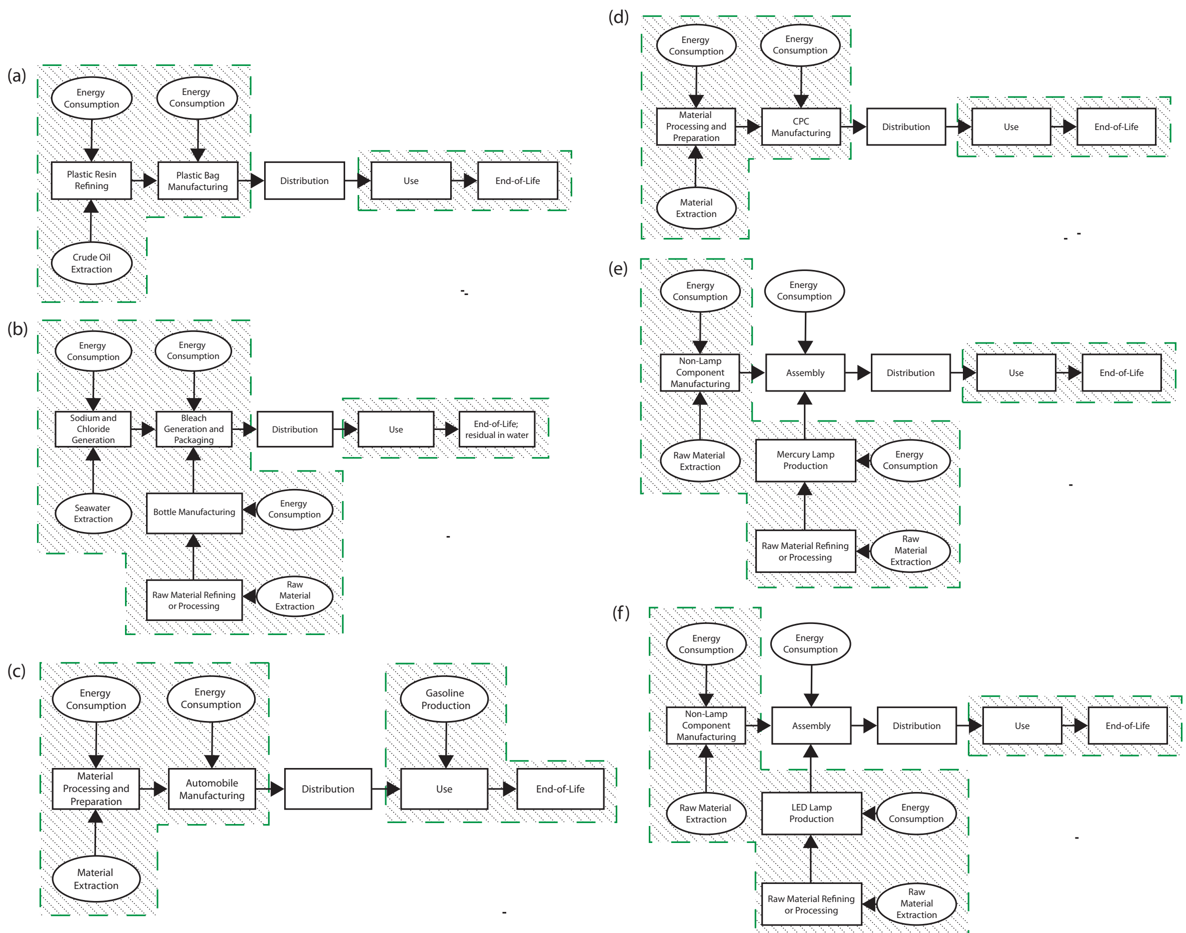

Figure 5.1. System boundaries for the studied treatment methods: (a) water delivery by truck, (b) chlorine, (c) SODIS, (d) CPC, (e) LP lamp reactor, and (f) LED reactor.

5.3.2 Life Cycle Inventory

The development of a life cycle inventory relied on three primary sources of information: existing literature, company documentation (websites and product manuals), and direct inspection of equipment. Analysis of each disinfection method was largely limited to the materials comprising the unit. This is not a complete representation of the total life cycle impacts of each disinfection system; however, it serves the purposes of this exploratory analysis by providing insight into the minimum impacts associated with each system. Material impacts are described as the "minimum" impacts of each system, since these impacts are independent of the manufacturing process, which could vary by factory and location.

The initial inventories for the indirect reactors were set up with company-provided information; the systems were then disassembled and the components were weighed to verify each inventory. The components of the CPC were weighed as parts and scaled up for the desired size of the reactors for each production rate. Existing literature was used to identify materials for SODIS reactors, chlorine, and water delivery. The EPA Municipal Disinfection life cycle analysis was used to support life cycle inventory of the low-pressure mercury lamp system.

None of the inventories included upstream treatment of water, such as particle settling or filtration. These treatment processes were assumed to be highly dependent on water source, largely independent of the disinfection process choice, and therefore inconsequential for disinfection system modeling. Additionally, inventories presented do not include chlorine dosing for residual disinfection; results were not sensitive to this assumption.

5.3.3 Life Cycle Impact Assessment (LCIA)

Life Cycle Analysis was conducted on SimaPro LCA Multi-user, version 9.1. Characterization was used to conduct Life Cycle Impact Assessment (LCIA). Characterization is a form of impact assessment that equates each pollutant with a "characterization factor," a general category of impacts characterized by a single pollutant equivalency. This study employed the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.0, a characterization method designed by US EPA. The impact categories and equivalencies are shown in Table A.1.

5.4 Results and Discussion

This material LCIA was conducted to compare the environmental and sustainability impacts of different water disinfection methods commonly used in low-income settings to better inform selection of such unit processes. LCIA results were compared across community (1000 LPD), school (500 LPD), small group (100 LPD), and family (30 LPD) scales. The analysis was applied over several system lifetimes (1 yr, 5 yrs, 10 yrs and 20 yrs). Results herein were normalized by the maximum value within each impact category under the given set of conditions for time span and water production. Thus, a normalized impact of 1 indicates the maximum impact in that category by any studied disinfection method for the given set of conditions. All normalized results presented were derived from impacts per liter of water produced by each system over its lifetime.

5.4.1 Water delivery, CPC, and chlorination raise environmental and social sustainability concerns

Figure 5.2 illustrates the overall impact of the studied disinfection methods under all of the production rates ((a) 30 LPD, (b) 100 LPD, (c) 500 LPD, and (d) 1000 LPD) for a one-year lifespan in Santiago de los Caballeros, Dominican Republic.

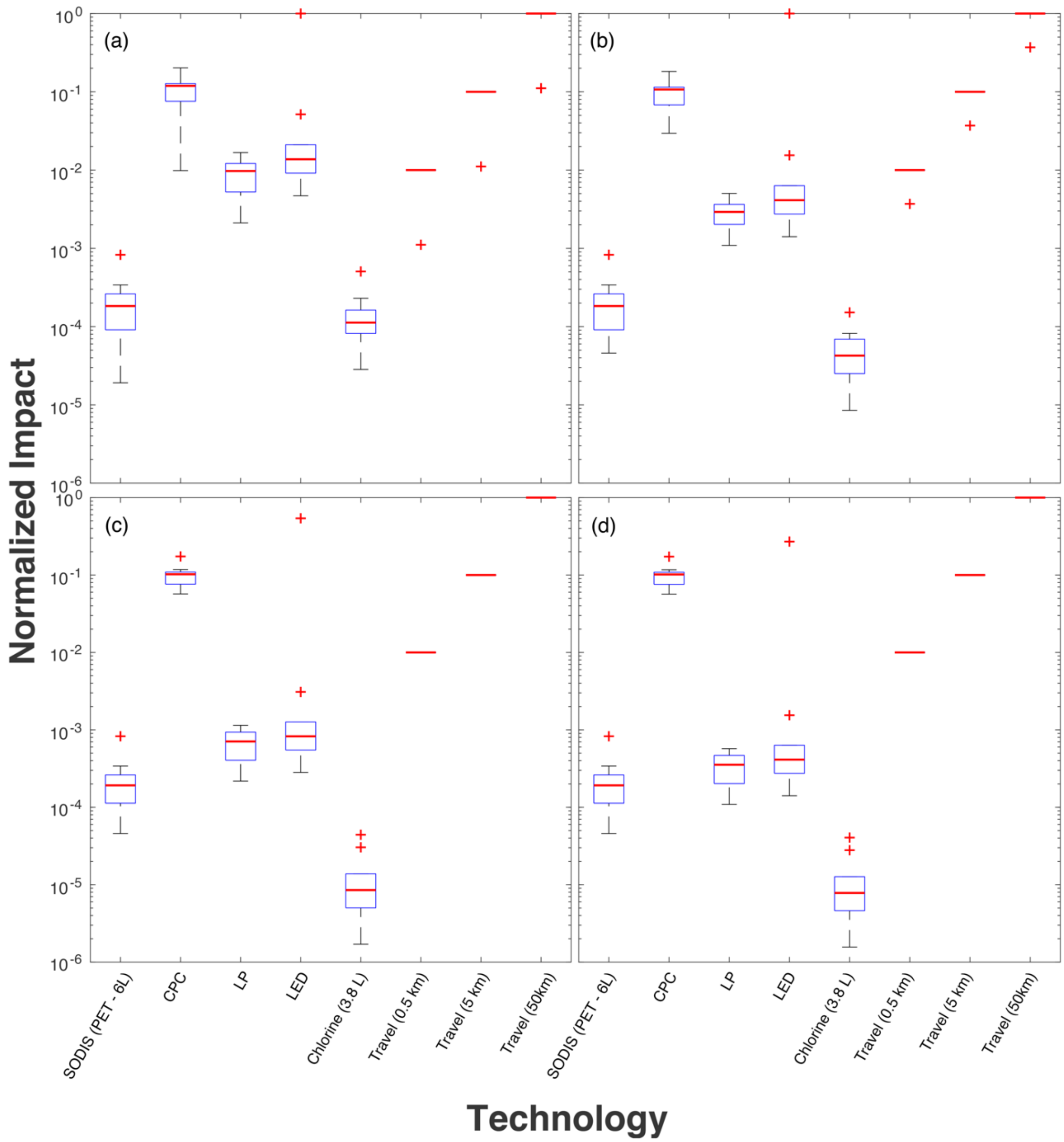

Figure 5.2. Comparison of the normalized impact in all TRACI 2.0 impact categories for each disinfection option (SODIS (PET – 6L), CPC, LP lamp, LED lamp, chlorine (3.8 L), travel (0.5 km), travel (5 km), and travel (50 km)) in Santiago de los Caballeros, Dominican Republic for a one-year lifespan at a) 30 LPD production, b) 100 LPD production, c) 500 LPD production, and d) 1000 LPD production. The box plot for each technology represents the range of the normalized impacts in every impact category for that technology under the given set of conditions, where red plus signs (+) represent outliers and red horizontal lines (–) represent the median values. A normalized impact of 1 represents the greatest impact. Note that the normalized impact axis is presented on a log_{10} scale.

Results of this analysis indicate that water delivery, particularly over long distances, had the greatest environmental impact in most categories, and thus was the least sustainable solution, even over this relatively short lifespan (one year). Travelling 50 km/day had an impact that was between 1.5-4 orders of magnitude higher than the next worst performing technology (CPC) in all impact categories except ozone depletion. The only travel distance studied that was competitive with the other technologies was 0.5 km/day, which is not a realistic travel distance to consider, since distances between collection and distribution at a centralized point have been reported to range from 2.9 – 60 km one way (Sikder et al., 2020). This limited travel distance would also severely limit the customer base of the person delivering the water, ultimately impacting long term economic sustainability of this solution. Based on this analysis, when given the option, water delivery by truck should be considered only when no other alternative is available.

The CPC was the next worst performing technology in most impact categories, with impacts around 2 orders of magnitude greater than the LP reactor, LED reactor, and SODIS at all production rates and roughly 3 orders of magnitude greater than chlorination at production rates of 500 and 1000 LPD.

These same trends for both travel and the CPC were observed over all time periods up to the maximum studied duration of 20 years, as seen in Figure 5.3. For this duration, the normalized impact of 50 km travel increased to 2-5 orders of magnitude higher than the other available technologies, and the impacts of the CPC were still 1-3 orders of magnitude higher than the remaining technologies at 500 and 1000 LPD. Based on these persistent trends, both the CPC and water delivery were excluded from further comparison.

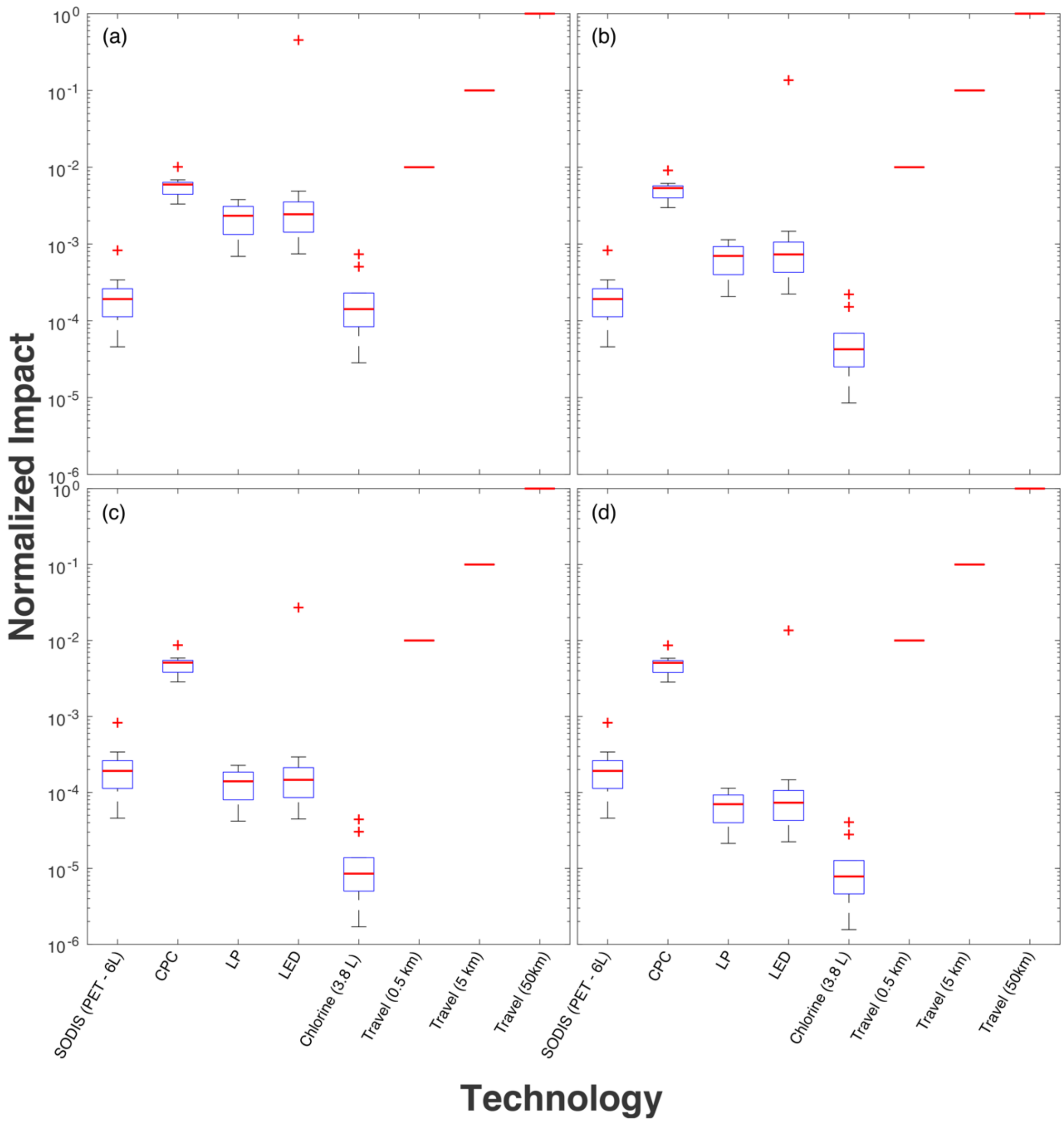

Figure 5.3. Comparison of the normalized impact in all TRACI 2.0 impact categories for each disinfection option (SODIS (PET – 6L), CPC, LP lamp, LED lamp, chlorine (3.8 L), travel (0.5 km), travel (5 km), and travel (50 km)) in Santiago de los Caballeros, Dominican Republic for a 20-year lifespan at a) 30 LPD production, b) 100 LPD production, c) 500 LPD production, and d) 1000 LPD production. The box plot for each technology represents the range of the normalized impacts in every impact category for that technology under the given set of conditions, where red plus signs (+) represent outliers and red horizontal lines (–) represent the median values. A normalized impact of 1 represents the greatest impact. Note that the normalized impact axis is presented on a log_{10} scale.

Chlorination was the lowest impact disinfection method under all studied conditions (Figure 5.4). In fact, this result was robust even to extreme conditions outside the normal range tested, where chlorine still outperformed UV disinfection by most metrics up to 10,000 L/day for 20 years. Only the smallest bottle (0.15 L) resulted in higher impacts at this scale. At 30 LPD, the normalized impact of SODIS (PET – 6L) in Santiago de los Caballeros, Dominican Republic is within ± 2.0% in all categories, with all but two (ozone depletion and respiratory effects) having higher impact than chlorine when 3.8 L chlorine bottles were used. This trend remained constant when different chlorine bottle sizes were assessed. At 30 LPD, the normalized impact of SODIS (PET – 6L) in Santiago de los Caballeros, Dominican Republic was ≤ 4.0% higher in all categories for 1.9 L chlorine bottles and ≤ 8.3% for 0.15 L bottles. The difference between these two technologies increased with both production rate and lifespan, where at 1000 LPD for 5, 10 and 20 years, SODIS had the highest normalized impact in all categories except ozone depletion. This same trend was observed for the same technology comparison in Kolkata, India (Figure A.1) and Nairobi, Kenya (Figure A.2).

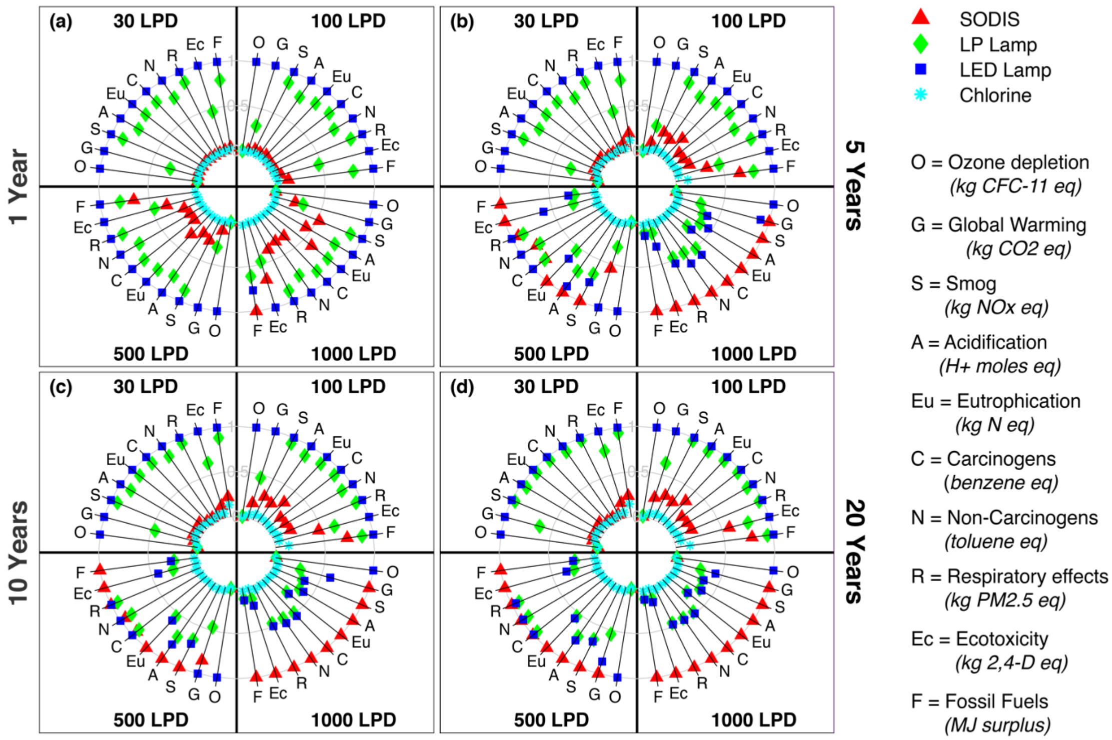

Figure 5.4. Comparison of the normalized impacts of SODIS (PET – 6L) (▲), the LP reactor (♦), and the LED reactor (■), and chlorine (3.8 L) (*) in Santiago de los Caballeros, Dominican Republic. Each quadrant (a, b, c, and d) represents the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent rates of daily water production within each lifespan. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the greatest impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

The trend for impact based on bottle size was time-independent, but varied based on the amount of water produced (Figure 5.5). At 30 and 100 LPD, the gallon (3.8 L) bottles had the greatest impact and the 0.15 L bottles had the least impact across most impact categories. At 500 and 1000 LPD, the 0.15 L bottles had the greatest impact in the most categories and the half-gallon (1.9 L) bottle had the lowest impact in the most categories. In particular, for fossil fuel depletion, 0.15 L bottles had a normalized impact of 0.22 at 30 LPD, which increased to 0.76 at 100 LPD, and at 500 and 1000 LPD it was the bottle size with the largest normalized impact (1). The reverse trend was seen for 3.8 L bottles, where the normalized impact was 1 for both 30 LPD and 100 LPD and decreased to 0.26 and 0.24 for 500 LPD and 1000 LPD, respectively.

For the 1.9 L bottle size, the normalized impacts in every category remained fairly consistent across production rates. At this bottle size, the normalized impact of fossil fuel demonstrated the greatest variation decreasing from 0.99 at 30 and 100 LPD production to 0.48 at 500 and 1000 LPD. Ozone depletion then increased in normalized impact of 27% between 30 LPD and 1000 LPD, while ecotoxicity decreased by 26% over the same production rate span. The remaining categories had less than 20% variation, with the normalized impact of acidification and eutrophication remaining nearly constant. Collectively, these findings indicate that bottle size plays a significant role in the environmental impact of chlorine, where choosing the wrong bottle size can increase impact by 40% or more.

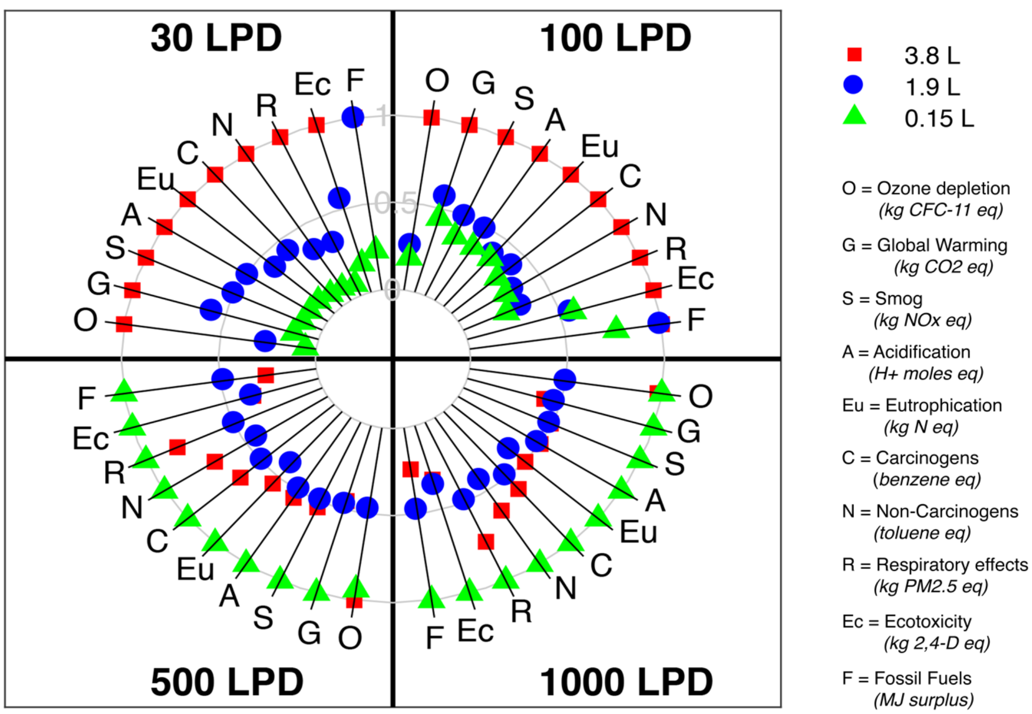

Figure 5.5. Comparison of the normalized impacts of chlorine based on the bottle size (■ 3.8 L, ● 1.9 L, and ▲ 0.15 L bottles) in Santiago de los Caballeros, Dominican Republic. Each quadrant represents the studied rate of daily water production (30 LPD, 100 LPD, 500 LPD, and 1000 LPD). The radial axes within each quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the most impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

This analysis indicates that chlorine has the lowest environmental impact of the studied disinfection technologies for water production under 1000 LPD for up to 20 years of the technology lifespan. Yet, chlorine adoption as a long-term water treatment method in low- and middle-income countries is often limited.[29] Studies to explore this dynamic – where chlorine is an effective, affordable, and readily-available form of water treatment, yet point-of-use (POU) adoption is not wide-spread – are ongoing and have not converged on the exact reasoning for lack of adoption. Studies to date often point to the adverse taste and odor of chlorine treatment products (Luoto et al., 2011; Sobsey et al., 2008), the difficulty to use compared to other technologies (e.g., filters) (Albert et al., 2010), and the required daily behavior change needed for point-of-use (POU) technologies (Luby et al., 2008). 55% of households in Bangladesh expressed, to an open-ended question, that the biggest obstacle to using chemical disinfectant products was their dislike of taste and smell of their water (Luoto et al., 2011). In another study comparing user adoption of POU water treatment technologies in rural Kenya, users reported ease of use as a reason they chose filtration over chlorination as their most preferred method of water treatment (Albert et al., 2010). Chlorination also requires users to continually repurchase a consumable product, which, if interrupted, may be difficult to restart water treatment again (Sobsey et al., 2008). While reasons may vary by individual and location, studies continue to show that adoption rates of manual chlorination fall drastically after study interventions to promote chlorination conclude (Pickering et al., 2015; Sobsey et al., 2008).

Both indirect treatment and SODIS treatment involve less direct interaction with water than traditional chlorine dosing and do not change the taste or odor of the treated water, potentially overcoming some of the mentioned issues with chlorine adoption. As a result, further analyses excluded chlorine to facilitate analyses and comparisons of the environmental impacts of UV-based alternatives.

5.4.2 Sustainability varies by application: Indirect UV Disinfection and SODIS

Figure 5.6 illustrates the normalized impacts of the LP lamp, LED lamp, and SODIS (PET – 6L) in each of the TRACI 2.0 impact categories. The LED lamp and LP lamp had the greatest impact at lower production rates (30 LPD and 100 LPD) over all time spans, whereas SODIS had greater impact at a production rate of 1000 LPD over long periods of time (i.e., over 5 years of use). The high impact of SODIS for high water production is a consequence of the large number of containers needed to scale this small, batch process (McGuigan et al., 2012), and the frequency that SODIS containers need to be replaced (typically after a few months) (Fisher et al., 2008).

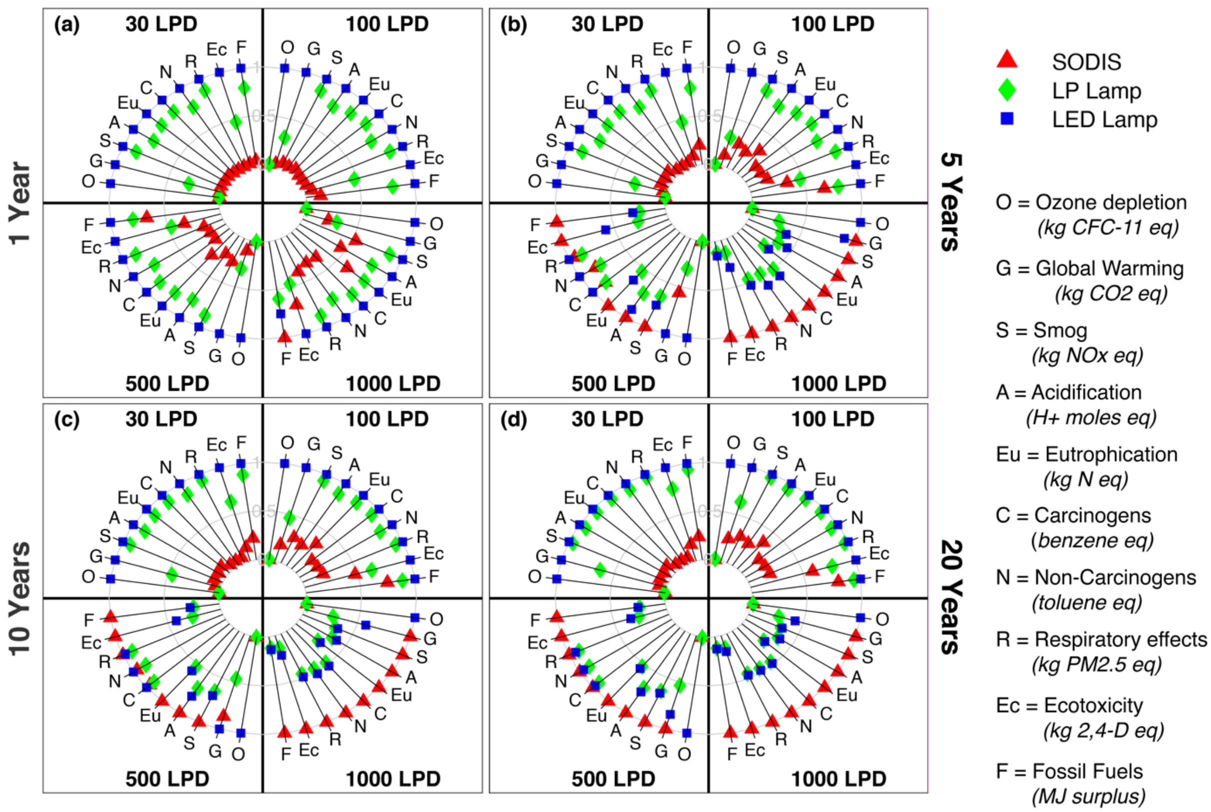

Figure 5.6. Comparison of the normalized impacts of SODIS (PET – 6L) (▲), the LP reactor (♦), and the LED reactor (■) in Santiago de los Caballeros, Dominican Republic. Each quadrant (a, b, c, and d) represents the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent rates of daily water production within each lifespan. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the most impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

These trends are, for the most part, consistent across different locations. Figure A.3 shows the normalized impacts for Kolkata, India, which vary only slightly from the results presented for Santiago de los Caballeros, Dominican Republic. Figure 5.7 shows the normalized impacts for Nairobi, Kenya, which show improved performance for SODIS in the 10 year, 500 LPD conditions. This is due to the increased amount of available ambient radiation near the equator and the increase in sunny days in the region compared to the other locations studied. Additional sunny days correspond to fewer bags needed, since less water is stored for cloudy days.

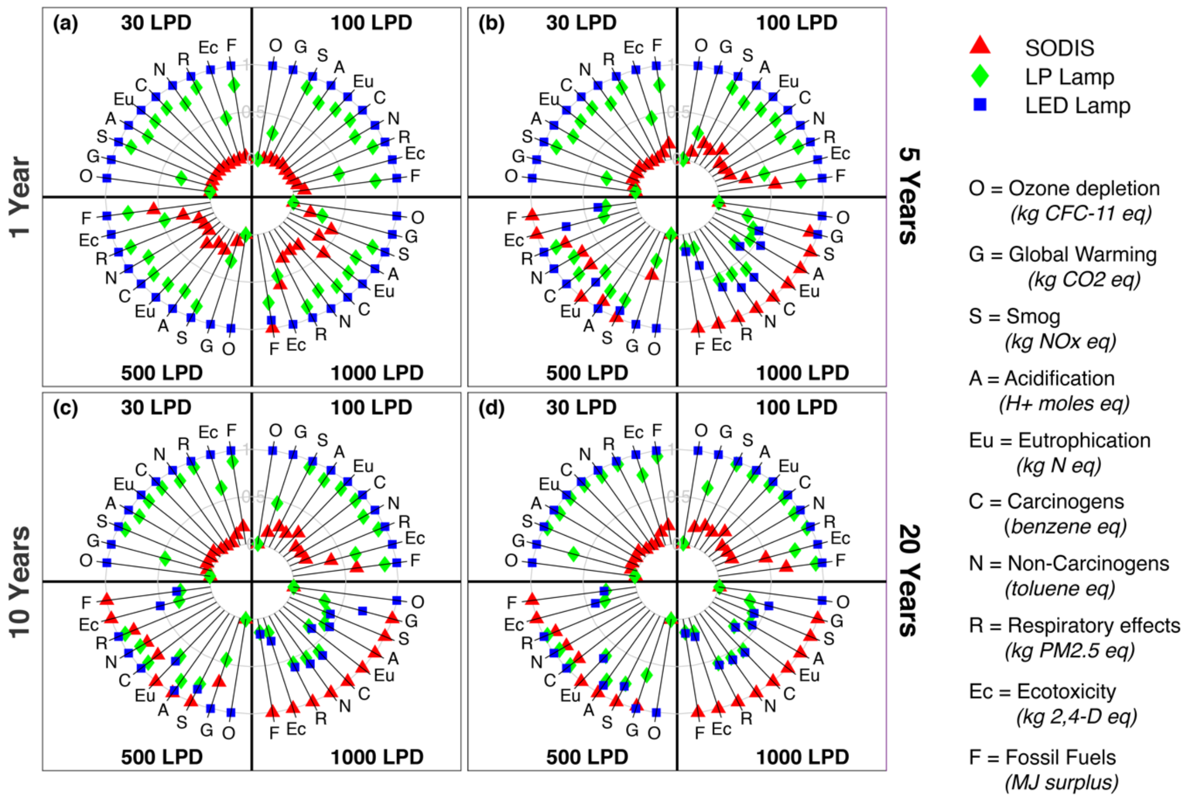

Figure 5.7. Comparison of the normalized environmental impacts of SODIS (PET – 6L) (▲), the LP reactor (♦), and the LED reactor (■) in Nairobi, Kenya. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the most impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

These results suggest that the most environmentally friendly alternative technology to chlorine for long-term, community-scale water disinfection, based on currently available technologies, would be the LP lamp system. The effectiveness of LP lamp systems in-context requires additional study; for example, the necessity of warm-up time for LP lamps means that users must budget additional time for water treatment, and use before warm-up is complete could endanger water quality. These complications are eliminated with instant-on LED lamps. Furthermore, mercury lamps, which must be replaced after 9000 hours in use, contain mercury, which needs to be properly disposed, and this disposal may not be available in low-income settings. Removing US end-of-life disposal from the analysis only improves the relative environmental impact of the LP and LED lamps in comparison to 6L PET SODIS bags at 500 and 1000 LPD for 10 and 20 years (Figure A.4); however, this does not account for human health and ecotoxicity risks of mercury release outside hazardous waste disposal facilities.

5.4.3 Potential improvements to SODIS materials

As discussed, SODIS bags were already selected for their increased disinfection performance in comparison to bottles. Another option to improve the SODIS process includes changing both the material and size of the bags. Figure 5.8 illustrates the normalized impact of three potential SODIS materials (PET, PP, and PMMA) for 1 L containers being used in Santiago with 216 cloudy days. The highest and lowest estimates of material lifespan were considered - PP is 30-150 days, PET is 150 days, and PMMA is 365-730 days – and end-of-life was considered the landfill.

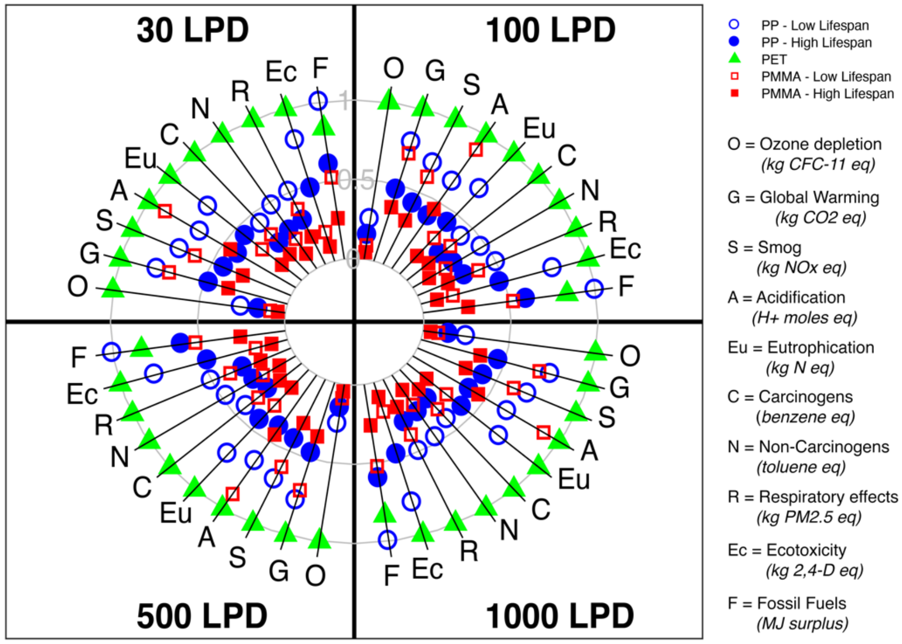

Figure 5.8. Comparison of the normalized impact of SODIS based on bag material for 1 liter containers (○ PP – shortest lifespan, ● PP – longest lifespan, ▲ PET, □ PMMA – shortest lifespan, ■ PMMA – longest lifespan) in Santiago de los Caballeros, Dominican Republic. Each quadrant represents the studied rate of daily water production (30 LPD, 100 LPD, 500 LPD, and 1000 LPD). The radial axes within each quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the most impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

The normalized trends across impact categories and production rates were time-independent, thus indicating that PET is the worst performing material in most impact categories, followed by PP. The best performing material in most impact categories was PMMA. This trend remained the same across locations (Nairobi and Kolkata). Therefore, PMMA could be used as an option for future SODIS containers to improve their environmental impact. The container size should also be considered when aiming to improve the environmental impact of the SODIS containers because of the 1 L, 4 L and 6 L containers, the 6 L container had the least impact in all impact categories. Using 4 L and 6 L PET bags instead of 1 L reduces the impact in every category by 21% and 24%, respectively.

Figure 5.9 illustrates the comparison of SODIS, the LP lamp system, and the LED lamp system when the SODIS bags are made from PMMA (assuming the longest possible lifespan of 730 days) with a volume of 6L. Under this set of conditions, SODIS becomes a feasible option for water treatment at all of the studied scales. This trend improves with an increased amount of available ambient radiation near the equator and the increase in sunny days in the region, when Nairobi, Kenya is considered (Figure A.5).

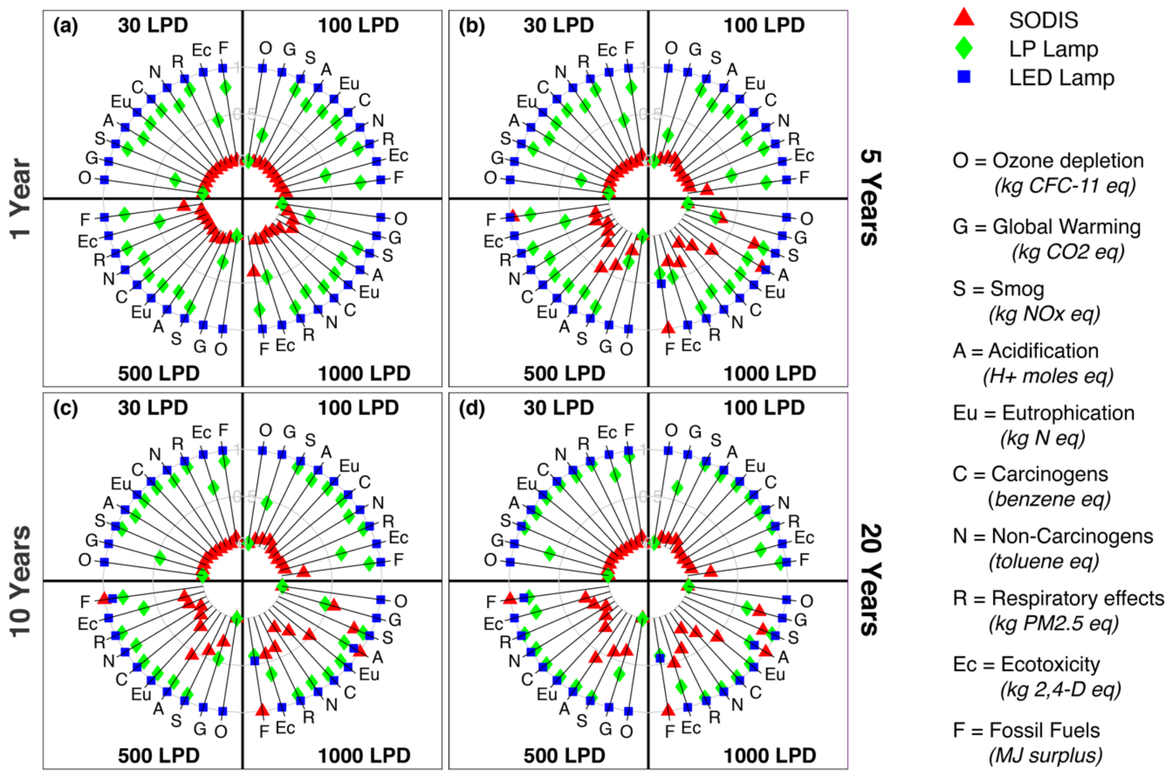

Figure 5.9. Comparison of the normalized environmental impacts of SODIS (PMMA – 6L – 730 day lifespan) (▲), the LP reactor (♦), and the LED reactor (■) in Santiago de los Caballeros, Dominican Republic. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the most impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

It is important to consider though, that many developing countries have started to ban plastic bags after Bangladesh established that 80 percent of the waterlogging in cities during floods was due to polyethylene bags blocking drains, resulting in higher prevalence of mosquitos and associated disease (United Nations Environment Programme, 2019). SODIS bags may therefore be harder to obtain and would be contributing to a known solid waste problem. SODIS adoption is also limited by the time required to treat sufficient quantities of water (Sobsey et al., 2008). Therefore, work should be conducted to study the feasibility of production of this type of product before it can be considered a viable alternative to the other disinfection options.

5.4.4 End-of-Life

This analysis was conducted using standard end-of-life practices for the United States. In most developed countries, end-of-life for solid non-food waste falls into one of several categories - recycling, combusting, or landfilling (EPA, 2019). Traditional life cycle analysis takes this into account in a variety of ways, usually considering the fraction breakdown of each material by disposal method and assigning that in the software. End-of-life in rural, developing areas can be quite different due to a lack of well-established solid waste management practices and limited regulations for hazardous waste (Mundada et al., 2004). Disposal of an expired good can range from open disposal to direct reuse or resale based on the resource value of the waste (Wilson, 2007). Waste streams in LDCs also vary widely in composition from 0 – 70% recyclable material and 17 – 80% organic material. The variability leads to varying waste management systems and recovery rates, which can range from 5 – 40%. Recycling in LDCs is a function of government policy, government finances, waste characterization, waste collection and segregation, household education, waste management administration, waste management personnel education, a waste management plant, the local recycled-material market, technological and human resources, land availability, and the relationships between these factors (Troschinetz and Mihelcic, 2009). Thus, the variability in end-of-life destinations specific to a given scenario supports the importance of assessment of life cycle impacts beyond traditional LCA. If decentralized solutions are going to be considered for international development, the material impacts of those systems both during and after their useful life, in the setting in which they are installed, will need to be considered.

5.5 Conclusion

These normalized performance results can serve as an initial matrix for assessing which technology may fit the specific set of constraints for a given scenario. The feasibility of each technology is sensitive to the alternative technologies available, the expected lifetime of the technology and the rate of production for which it will be used. Water treatment system design at the household- and community-scale in LDCs should include a variety of considerations, including social acceptability, ease of use, and longevity of intervention. At the scale necessary for universal access to safe water, rollout of these technologies is likely to have significant environmental impact implications, and our results suggest that these impacts vary substantially by intervention. In particular, we find that simple chlorine dosing is the most environmentally friendly solution to water disinfection at scales lower than 1000 LPD, but the social sustainability of this solution is unclear. Beyond this, LP lamp systems powered by simple solar panel and battery systems represent the next best solution for community-scale water treatment, though their end-of-life ramifications are significant when not properly disposed. Accordingly, we conclude that both forms of indirect UV disinfection are worth further study in the context of household- and community-scale water treatment in LDCs, and we highlight the importance of additional work on the social sustainability and end-of-life characteristics of these interventions. Only with this sort of multi-faceted analysis can the effectiveness and sustainability of safe water interventions globally be understood. We contribute to this ongoing work with a first of its kind comparison of disinfection technologies specifically suited to these complex design environments.

CHAPTER 6. Lessons Learned through the Installation of Water Treatment systems in the Dominican Republic Through an Interdisciplinary, Student-Led, Service-Learning Course

6.1 Abstract

Access to safe drinking water is recognized as a basic human right, yet 785 million people globally still lack access to an improved water source. Further, the term 'improved water' is not synonymous with "safe water," leading to an underestimation of the actual number of people without access to a safe source of drinking water. Efforts to address this have focused primarily on household water treatment (HWT) systems, placing the burden for safe drinking water on individuals, which has proven to be an ineffective strategy. An interdisciplinary service-learning course at Purdue University was developed to address this issue in the Dominican Republic by focusing on the implementation of community-scale water treatment. Since the course began, drinking water treatment systems have been installed in four primary schools within the La Vega region of the Dominican Republic. These systems can provide safe, potable water at the schools, which are a central location to their respective communities both geographically and socially. Yet, key barriers such as system downtime when school is not in session, economic constraints of public schools in the DR, and preferences of water aesthetics have prevented full adoption of the systems.

6.2 Introduction

The Dominican Republic (DR) has struggled to make country-wide progress towards providing safe drinking water for all of its residents (Baum et al., 2014). Improved water has been used as a metric by the Sustainable Development Goals (SDGs) to track progress toward providing a greater fraction of the population with access to drinking water. But 'improved' is only defined as a piped water source inside the user's dwelling, plot or yard, public taps or standpipes, tube wells or boreholes, protected dug wells, protected springs and rainwater collection (United Nations, 2012). It does not require that the water has been appropriately treated to remove or inactivate waterborne pathogens. As an illustration, in the Puerta Plata region of the DR, 47% of improved water sources tested high to very-high risk for *E. coli* (Baum et al., 2014). So even though 90% of the DR population had access to an improved water source in 2017 (UNICEF/WHO, 2019), it is expected that a much lower percentage of the population had access to microbiologically safe drinking water.

Water disinfection technologies designed to overcome this issue have focused primarily on low-cost, point-of-use (POU), household water treatment (HWT) solutions including chlorination, filtration, boiling, flocculation/disinfection and solar water disinfection (SODIS) (Clasen et al., 2007; McGuigan et al., 2012; Sobsey et al., 2008). It is also a popular practice for homes to receive treated water by truck delivery (Sikder et al., 2020; Treacy, 2019). Unfortunately, POU HWT places burden on individuals to manage and sustain their own access to safe water. Often this requires behavioral change as individuals adapt their daily habits around water usage, which studies have shown can be challenging. Post-study compliance rates for HWT technologies such as chlorine, coagulation/chlorination, and SODIS show that long-term usage of such technologies are low, often falling below 10% (Sobsey et al., 2008).

Technologies that require only one-time purchase and little user effort for providing sufficient water can promote long-term usage (Sobsey et al., 2008). One way to utilize current technologies while meeting these requirements is to install decentralized, community-scale systems, which are often perceived to save time and be less burdensome than HWT options (Cherunya et al., 2015). For example, in Dhaka, Bangladesh passive chlorination systems at the decentralized, community-level resulted in more households with stored, chlorinated water (60%) than in households with POU Aquatabs (40%) after a 6-month study period. Further, sustained use of the passive chlorinator did not require continued intervention, whereas 50% of Aquatab users immediately stopped using the POU treatment when the behavioral intervention from the study concluded (Pickering et al., 2015). However, community-scale systems still fail, often due to slow implementation and lack of maintenance (Varghese, 2004), which is often a result of lack of properly trained operators and an insufficient supply chain for system replacement parts (Wright and Winter, 2014). Successful systems observed by (Wright and Winter, 2014) had both paid, well-trained local operators and available technical support for any issues that arose with the systems.

The work herein describes the process of trying to address these barriers faced by community-scale water treatment systems by installing them in primary schools in the DR through a student-led, service-learning model. School-based systems were intended to allow for the water systems to be operated within an existing local construct where people gather. This structure was also intended to drive system sustainability as the schools would be able to sell excess water and fund local system operators. The service-learning course structure was intended to improve short- and long-term communication with communities, improve training of local operators, as well as provide technical support while the systems were being adopted. Ultimately, the goal was to establish sustainable water treatment systems that would be used by each community to provide access to safe, affordable water and to do so by providing appropriate training and resources to facilitate locally managed and operated systems independent of the class.

6.3 Methods Project Structure

In 2012, the Water Supply in Developing Countries course was established at Purdue University to work toward providing safe, affordable drinking water to rural communities of the DR. This course was developed to implement the academic service-learning model (Howard, 1998) in an interdisciplinary, student-led environment, where both undergraduate and graduate students participate in the design and holistic implementation of water treatment systems in partnership with the recipient communities. This integration is summarized in Figure 6.1.

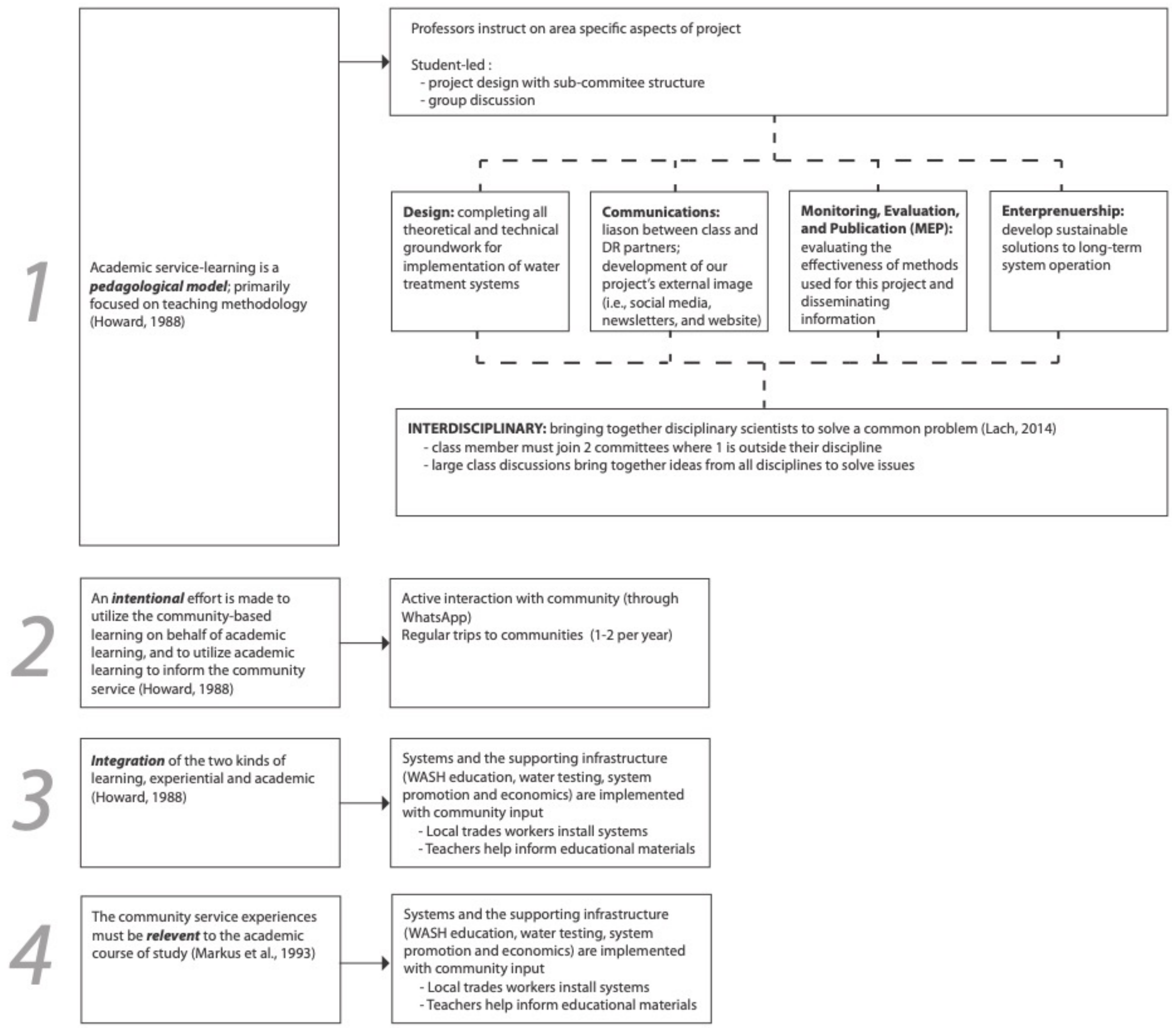

Figure 6.1. Schematic of the class structure and how it correlates with the academic service-learning model (Howard, 1998; Markus et al., 1993) and incorporates interdisciplinary problem solving (Lach, 2014a).

1) The service-learning model is a pedagogical model focused on teaching methodology (Howard, 1998). This pillar of the model is established though a student-led, interdisciplinary structure where professors provide lectures on their areas of expertise within the project and general project oversight, while students work in peer-led committees across disciplines to develop and implement the project. These committees focus on design of the systems, communicating with project partners, monitoring and evaluation of the project, and enterpreneuership efforts to promote longevity of the systems. Students in the class are required to join two committees, where at least one is outside of their primary academic discipline.

Further, the interdisciplinary approach was designed with the goal of holistic implementation, which considered community input into system design, the long-term economic sustainability of system, education around safe water its public health implications. Herein the installation process for these systems is detailed; analysis of project economics and health education are outside the scope of this manuscript.

2) An intentional effort is made to use community-based learning for academic learning and vise versa (Howard, 1998). This is carried out through continual communication with communities for input and feedback. The class has maintained communication with community partners through WhatsApp, and has participated in 1-2 trips to the project sites each year. On each visit, class members meet with every community whether work is being conducted on their system or not, at the time.

3) Two types of learning must be integrated (Howard, 1998). By working with communities in system design and impelmentation of the systems, both community- and academic-learning are combined. School officials, as well as parent and teacher groups, are consulted about system design and ideas for system usage and long-term sustainability. Further, local tradesworkers collaborate with the class to implement systems using their knowledge of the trade and the area.

4) The service experience must be relevant to the academic learning (Howard, 1998). This goal of this course is to develop sustainable, community-scale water treatment systems for low-income communities in the Dominican Republic, and the experience of designing and implementing these types of systems provides relevant, real-world experience toward achieveing this goal.

This approach was designed to overcome key issues with the adoption of community-scale water treatment systems in developing countries, by creating a consistent structure of collaboration and communication between the class and the recipient communities.

6.3.1 System Locations

Primary schools were selected as installation points to utilize their location as a community center and to promote consistent usage of the systems. This approach also employs the approach of children as agents-of-change (Bresee et al., 2016; Onyango-Ouma et al., 2005; Wingert et al., 2014). In previous WASH related studies, mothers have indicated that they have high levels of trust in health information that their children communicate from school (Bresee et al., 2016), and communication of this information from children to adults has led to an improvement in health related knowledge in both groups (Onyango-Ouma et al., 2005). Therefore, by placing the systems at schools, the class works within this centralized structure to promote the importance safe drinking water to students, who can pass this information on to their families and community.

Factors that were considered in country selection were the need for safe drinking water in the location, the stability of the political climate, and the ability to travel to target communities to maintain communication throughout the service-learning project. Based on these considerations, the initial funding partner AquaClara International, suggested that work be focused in the Dominican Republic (DR), and they made introductions with the main point of contact in-country, Joe (name has been changed for confidentially purposes). Joe is a local leader in the La Vega region of the DR, and he worked with us to identify local primary schools with existing water storage infrastructure that could support a water treatment system.

After the first installation, the class partnered with the Lafayette, IN Rotary Club and Rotary International to install three more systems. Joe worked to identify schools for potential systems that were within driving distance from the original system, which also had existing water storage infrastructure. This was done to create a network where the schools could provide support to each other, and to provide the opportunity for a centralized maintenance structure (if the schools wanted to establish one). One of the class trips to the DR was used to prioritize schools for development of water treatment systems. The initial decision was made based on a cost-matrix of important characteristics for installation, including the need for water treatment system, level of school engagement and interest in the project, and the amount of work required to install a system at each site. From experience with the first installation, school engagement and interest in the project were weighted heavily as priorities for installation. Final decisions on installation order were made based on the engagement of the community and willingness to communicate while the class was not in-country.

6.3.2 Community Baseline Surveys

Surveys were conducted with community members to collect information on the local demographics and current water and health practices. Survey results were used to inform system design. Additional data were collected through structured interviews led by local volunteers who were trained as enumerators. Enumerators were trained on interviewing methods; the software used to collect data on provided tablet computers was presented in their native language of Spanish. After training, enumerators practiced leading interviews and collecting data with each other before traveling to households within the survey area to conduct interviews. Survey participants were provided the option to skip any of the questions. Enumerators were paid for their time based on local wages on a per survey basis. The surveys conducted were approved by the Purdue Institutional Review Board (IRB) (IRB-1212013029 and IRB-1711019911).

6.3.3 Treatment Systems

The implemented water treatment systems conform to the multiple-barrier concept to include redundant processes for physical separation of particles and disinfection (Hrudey and Hrudey, 2004). Systems that follow this approach can provide potable, affordable water along with the resiliency required for public water systems.

Funding

Initial system installation and startup was funded by research grants and other funding obtained by the class. After start-up support, the goal was for the systems to be fully operated and maintained by each community independent of external support through sales of excess treated water to the surrounding community. This was intended to promote community-wide acceptance and investment in the water treatment system.

Construction

Cooperation and engagement from local communities is also essential to system sustainability (L. W. Gill and Price, 2010). Thus for construction of the systems, local trade workers were hired and consulted to complete installations. The schools were asked to identify local trusted electricians and plumbers. Due to the close proximity of the schools and strong community relationships, the same trades workers were able to work on all of the systems, which facilitated installation and improved troubleshooting due to experience with the project.

Operation and Testing

One or more operators of each system were selected by each school at which a system was installed. These individuals were trained in the operation of the system, and provided water testing equipment for use in routine monitoring of product water quality. As parts of the training in system operation, one-page descriptions of each system component, instructional videos of tasks need to operate and maintain the system, as well as in-person training were provided.

6.4 Pilot System Installation and Iteration

The first system was designed to treat groundwater provided to School 1 by a local community member's well. Community members suggested the use of this supply given its proximity to the school where the system was to be built, as well as the agreement by the owner of the well to make water from the well available for the project. Water was pumped from the well when electricity was available and when the school's water tanks were near empty. Water then flowed through a sand filter and a 5-micron cartridge filter to two storage tanks where a float valve closed when the tanks reached capacity. At this point, the water was manually chlorinated and allowed to sit for at least 30 minutes before accessing the treated water through the taps at the bottom of each tank.

The first iteration of this system was used only sparingly by the community, and community members described the reason to be a result of the taste of the effluent water. They described the taste as not "sweet" like the water they were accustomed to drinking, which could be associated to an aversion to the taste of the hard groundwater (Whelton et al., 2007) and/or residual chlorine from treatment (Crider et al., 2018a). Therefore, the water source was converted from groundwater to rainwater, which was collected from the roof of the school using a gutter system. A pump was installed to pull this water from the rainwater collection cistern to an elevated tank, located on the roof of a building on the school property, to allow for gravity-fed water treatment.

To address the potential adverse taste of chlorine, the manual chlorination process was evaluated. This was determined to be an ineffective method for chlorination within this system because the batch design made it difficult to determine the quantity of bleach needed in the system at a given point in time. Electrical intermittency meant that water could only be added to the system when the grid was running, and this did not always correlate with the system tanks being empty. Therefore, the operator could not determine the amount of chlorine needed in the system at any given time. To overcome this, the Zimba automatic chlorination system (https://zimbawater.com/) was included immediately before the storage tanks to dose 5-gallon batches of treated water with chlorine before they were released into the storage tank. This system has proven to be simple yet effective because it has no moving parts, is gravity fed, requires infrequent refilling with chorine (once per week under anticipated use conditions), and applies chlorine in a sequencing-batch process that can operate in a continuous manner.

A UV reactor utilizing a low-pressure (LP) Hg lamp, was installed before chlorination for initial disinfection and for an additional barrier against protozoan parasites that are not effectively inactivated by standard chlorination (Rochelle et al., 2002). The addition of UV treatment also allows for dosing of chlorine at residual levels (0.2-0.5 mg/L), which are lower concentrations than standard chlorine dosage (2-6 mg/L), ultimately improving the taste and odor of the effluent water.

In the new configuration, water from the elevated tank flows by gravity through a sand filter, then to a 5-micron filter, followed by UV treatment and automatic chlorination with a Zimba system before use (Figure 6.2).

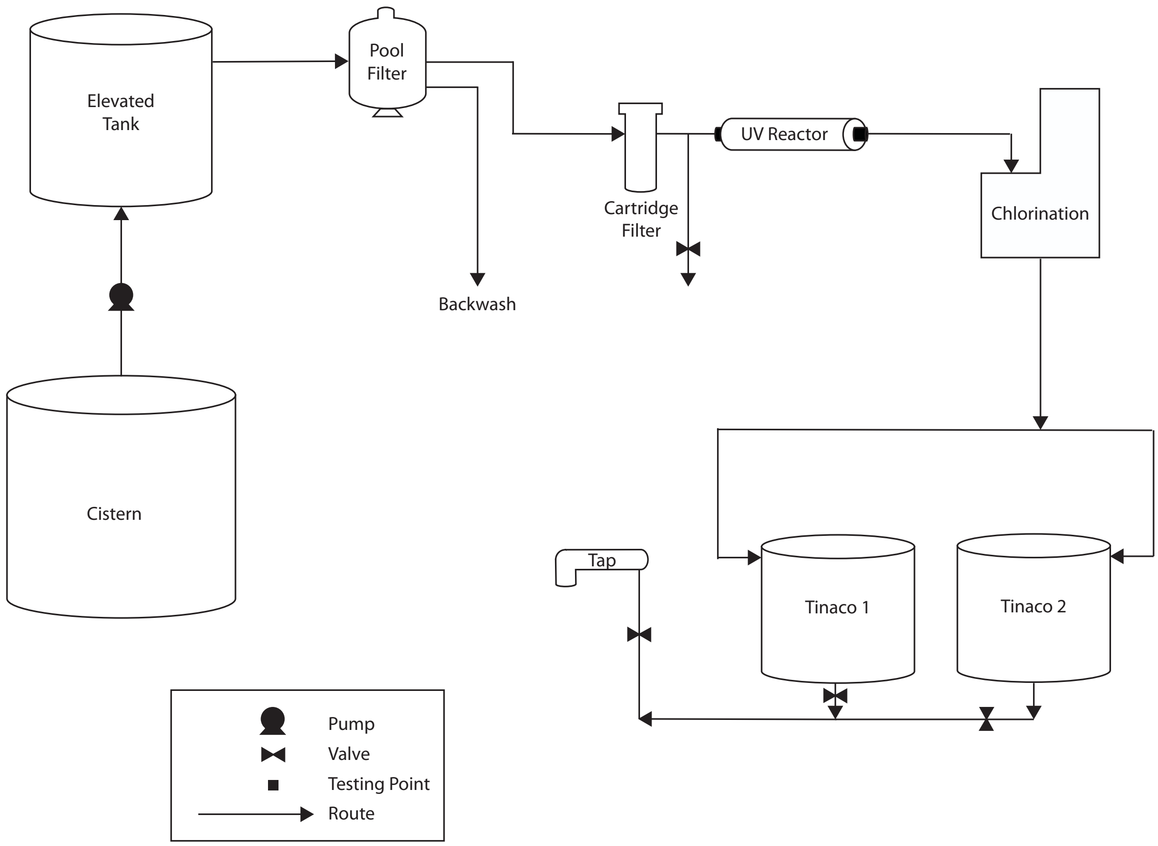

Figure 6.2. Flow schematic of water through the first water treatment system.

System Management

Multiple studies have highlighted the need for community involvement in and approval of interventions for the successful implementation of water treatment systems in rural areas (Ali, 2010; L. W. Gill and Price, 2010; Guchi, 2015a; Nauges and Whittington, 2010). To engage the community with the first system, a group of local community leaders was formed to represent community interests – this group termed themselves “El Patronato.” This group was selected by Joe and the school that was receiving the system. El Patronato was tasked with operating and maintaining the water system. This discrepancy between the decision makers for the system and the physical location of the system on the school grounds created confusion regarding who owned and was responsible for the system. For all subsequent systems that were implemented at public schools, each school was asked to choose their own leadership structure.

Detailed plans of new systems (or changes to the existing system) were provided to these groups for discussion and decision making. Communication about design took place through video calls (Skype, FaceTime and/or Facebook Messenger) to the schools while the class was in the United States, and directly in meetings with the schools while the class was in the DR. After these discussions, community and school leaders would often ask the class to make recommendations or decisions about the system design.

6.5 Community Baseline Surveys

Before each of the next system installations, oral community baseline surveys were administered by local enumerators. Respondents were provided the option to skip any question if they preferred not to answer. Table 6.1 summarizes some of these results specific to community demographics and water usage in the area.

Table 6.1. Results of the community baseline survey in School 2, School 3, and School 4. Percentages were calculated based on the total number of responses unless otherwise noted.

		Town/Locality		
		School 2	School 3	School 4
% of respondents that have children in primary school		38.4%	28.8%	68.1%
Where do you get your water?*				
Dry Season	Piped into dwelling	1.9%	6.5%	1.1%
	Piped into yard	0.0%	3.0%	0.0%
	Public well	17.6%	2.0%	0.0%
	Household rainwater collection	41.7%	9.0%	16.3%
	Trucks that fill cistern	14.8%	13.5%	4.3%
	Bottles delivered by truck	0.0%	1.5%	2.2%
	Bottles bought from store	61.1%	85.0%	83.7%
	Surface water	1.9%	0.0%	2.2%
	Other	0.0%	0.0%	0.0%
Rainy Season	Piped into dwelling	0.0%	13.0%	1.1%
	Piped into yard	0.0%	5.0%	0.0%
	Public well	15.3%	1.0%	0.0%
	Household rainwater collection	81.5%	40.0%	39.1%
	Trucks that fill cistern	0.5%	6.0%	3.3%

Table 6.1 continued

Bottles delivered by truck	0.0%	2.0%	1.1%
Bottles bought from store	42.1%	82.5%	72.8%
Surface water	0.9%	0.5%	1.1%
Other	0.0%	0.5%	0.0%
Average price for a bottle of water? (RD$)	39.31 ± 12.25	40.00 ± 2.69	40.47 ± 3.65
Who is in charge of collecting water at home?			
Adult female	4.6%	9.0%	14.1%
Adult male	12.0%	21.5%	35.9%
Both adult female and male	0.5%	5.0%	3.3%
Child under 15 years old	0.5%	0.0%	1.1%
How safe do you think the water is to drink? (7 being the highest level of security for which no additional treatment is necessary, with 1 being unsafe water that requires treatment before consumption.)			
1 – Extremely Unsafe	1.9%	10.5%	23.9%
2 – Very Unsafe	0.5%	5.5%	38.0%
3 – Unsafe	6.9%	6.0%	12.0%
4 – Not known	20.8%	9.5%	12.0%
5 – Safe	16.2%	26.0%	7.6%
6 – Very Safe	20.8%	28.5%	1.1%
7 – Extremely Safe	33.3%	14.0%	5.4%
How do you treat your drinking water?*			
Strain it through a cloth	0.5%	8.5%	13.0%
Boil	2.3%	8.5%	6.5%
Add chlorine	49.5%	20.5%	23.9%
Solar disinfection	0.5%	0.0%	13.0%
Filter	28.2%	2.5%	4.3%
Other	0.5%	0.0%	0.0%
Do not treat	21.8%	65.0%	45.7%
If you treat the water, do you drink water from any other source?			
No	35.0%	42.0%	72.7%
Yes	65.0%	58.0%	27.3%
How much do you spend on water treatment per month? (RD$)	71.99 ± 120.69	30.04 ± 20.82	164.63 ± 152.52

Table 6.1 continued

How do you store your water?			
Underground tank	15.7%	8.5%	7.6%
Permanent above ground tank	28.2%	12.0%	6.5%
Large blue plastic drum	33.3%	60.5%	81.5%
5 gallon bucket	8.8%	15.0%	3.3%
Do not store	2.8%	11.5%	0.0%

*Questions allowed for multiple answers, therefore total percentage of responses may exceed 100%.

Data from School 1 was omitted from the table because the survey was improved to include more detailed questions about water usage between installation in this community and the other three communities. For School 1, 51% of respondents used rainwater as their main source of drinking water in the rainy season, and 40% used bottled water. In the dry season, 36% used rainwater, 38% used bottled water, and 14% used protected boreholes (Alwang et al., 2017).

Results of this survey indicated that a majority of people in these communities obtain at least part of their drinking water by buying bottles from the store – 61.1%, 85.0%, and 83.7% in School 2, School 3, and School 4, respectively during the dry season and slightly lower percentages of 42.1%, 82.5%, and 72.8%, respectively in the rainy season. Interestingly, this does not correlate with consumers believing their water is safe. When asked to rank how safe they believe their water is on a scale of 1-7, where 7 is safe and does not need treatment, and 1 being extremely unsafe and must be treated before being consumed, consumers that bought water from the store only ranked the water as safe and not needing treatment (7) 35.6%, 15.3%, and 5.2% of the time in School 2, School 3, and School 4, respectively. These results, as well as rankings for safety of other water sources can be found in Table B.1.

The next most commonly used source of drinking water in every community was rainwater collection at the home. During the dry season, 41.7%, 9.0%, and 16.3% of respondents indicated that they get their drinking water this way in School 2, School 3, and School 4, respectively. During the rainy season these values increased to 81.5%, 40.0%, and 39.1%, respectively, in the same communities. 38.9%, 5.6%, and 6.7%, respectively of respondents indicated that they believe rainwater collected at their home is safe to drink with no treatment needed (7).

Though these results indicate that most people in these communities believe their water needs to be treated for it to be safe to drink, 21.8%, 65.0%, and 45.7% of respondents in school 2, school 3, and school 4, respectively did not treat their water before drinking. Conversely, in school 1, 81% of respondents reported that they treated their drinking water, with the majority using bleach (Alwang et al., 2017). When they did treat their water, chlorination was the most commonly used method of treatment in each community. Unfortunately, of those people that did treat their drinking water, 65.0%, 58.0%, and 27.3% of respondents in respondents in Schools 2, 3, and 4, respectively still drank water from another source other than the one they treated. Further, it is important to note that the majority of people stored water for some period of time (only 2.8%, 11.5%, and 0.0% did not store drinking water in Schools 2, 3, and 4, respectively), indicating that a residual (secondary) disinfectant is needed for safe water storage.

These results also indicated that many community members spend money on both purchasing water and water treatment. The price for a bottle of water in each community was very similar, ranging from 39.31-40.47 Dominican Pesos (USD$0.69-0.71) on average. Those treating their water spent, on average, 71.99 ± 120.69, 30.04 ± 20.82, 164.63 ± 152.52 Dominican Pesos or (USD$1.26 ± 2.21, 0.53 ± 0.36, 2.89 ± 2.67) per month in School 2, School 3, and School 4, respectively.

6.6 Additional System Designs

6.6.1 Source Water

Knowledge from the pilot system, as well as information from the baseline surveys, led us to adapt all of the future systems to utilize rainwater. Very few respondents used public wells in any season (wet or dry), and of those that did, less than 8% believed the water from this source was safe to drink. The potential rainwater collection capacity of each school was calculated based on rainfall data from the Oficina Nacional de Meterología (ONAMET) at two nearby locations and the footprint of each school. This was compared to the storage capacity at each school in existing cisterns. The responsibility for repair of these cisterns or adding addition for extra storage was agreed to be that of the schools. Schools that did not have enough storage capacity or the funds to build additional cisterns took the initiative to set up agreements with the local water delivery service CORASAAN to have water delivered during periods of insufficient rainfall.

6.6.2 Electricity

Due to the frequently unreliable source of electricity from the grid experienced at the first school, a solar panel array and battery system was installed at each school to ensure operation of the system components (i.e., pump, UV reactor) in the absence of electricity from the grid. This system comprised eight 6 V batteries and four 265 W solar panels. It was purchased from and installed by a locally certified solar panel technician. Electrical power generation from this system exceeded the requirements of the water treatment systems in each case; excess electrical power generated by the solar panel systems was used for in-school purposes, such as room lighting or operation of computers.

6.6.3 General System Design

The installed systems were powered by a solar panel and battery system, which provided reliable electrical power to operate a pump to move water from a cistern, through filtration, UV disinfection, and chlorination. The specifics of each system design can be found in Figure B.1, Figure B.2, and Figure B.3, for Schools 2, 3, and 4, respectively. It is important to note that the system for School 2 had multiple flow and storage options, which were accommodated by many valve configurations. This made remote troubleshooting system problems difficult, and therefore the configurations and number of valves were streamlined for systems at Schools 3 and 4.

Water storage containers were selected based on standard water storage practices in the area, which were large plastic tanks (referred to as "tinacos" locally). Tinacos were elevated to allow for gravity fed distribution of the treated water for drinking (Figure 6.3).

Figure 6.3. Elevated tinaco used to store treated water so that it can be gravity fed to drinking water taps and handwashing stations.

6.6.4 Community Involvement in Installation

The class members also invited students from each school to help make the system more approachable and understandable to students at the schools and to encourage ownership of the system. Students from each school painted illustrations around each system component to illustrate its function as well as the flow path of water through the system (Figure 6.4).

Figure 6.4. Illustrated map of water flow and system components designed by members of School 2 (left) and School 4 (right) to encourage students to learn about and engage with the system.

6.6.5 System Cost

To allow for ease of maintenance and to promote sustainability, the components used were sourced from local vendors and the systems were installed by a local plumber and electrician. The cost of the typical system components and their suppliers used are summarized in Table 6.2.

Table 6.2. Summary of system components and their associated costs in US Dollars.

System Component	**Brand**	**Supplier**	**# Used**	**Total Cost (USD)**
Plumbing Parts	N/A	Multiple		$415.00
Electrical Supplies	N/A	Multiple		$144.00
Pump				$45.00
Solar Power				
Solar Panels (265 W)	Megatone	Megatone	4	$480.00
Batteries (6V) Deep Cycle	Megatone	Megatone	8	$960.00
Double Throw Transfer Switch	Megatone	Megatone	1	$200.00
Inverter (2kW-2.5kW)	Megatone	Megatone	1	$1359.00
Charge Controller	Megatone	Megatone	1	$700.00
Pool Filter		Robeyda	1	$300.00
Filter Housings	Pentek	Robeyda	1	$252.00
1-Micron Filter (8)	Pentek	Robeyda	1	$15.00
5-Micron Filter	Pentek	Robeyda	1	$15.00
Automatic Chlorinator	Zimba	Zimba	1	$440.00
LP Hg Reactor	Viqua	Robeyda	1	$349.00
Quartz Sleeve*	Viqua	Robeyda	1	$35.00
Lamp*	Viqua	Robeyda	2	$79.00
Storage Tank (size)			2	$160.00
Labor				
Solar	Local Trade Worker			$180.00
Electrician/Plumber	Local Trade Worker			$190.00
Plumber	Local Trade Worker			$63.00
ESTIMATED SYSTEM COST				$6,381.00

*Replacement parts

Table 6.3 presents the upfront cost for the first year of testing supplies and indicates that this amount totals approximately 47% of the cost of the system. The turbidimeter, UV_{254} meter, ZenTest PC60-Z, and Android tablet represent one-time costs that would be amortized over their useful product lifetimes. The schools will need to purchase chlorine test strips and calibration solutions for the ZenTest PC60-Z as recurring costs. The recurring testing costs require a continual yearly cost of around $200 per year.

Table 6.3. Summary of system testing materials and their associated costs in US Dollars.

Testing Equipment	Brand	# Used	Total Cost (USD)
Turbidimeter	Hach	1	$1,337.00
Real UV254 Meter	RealTech Inc.	1	$1,098.00
Chlorine Test Strips (50 pk)	Industrial Test Systems	8	$131.00
ZenTest PC60-Z	Apera Instruments	1	$195.00
8 oz. pH/EC calibration solution kit	Apera Instruments	1	$70.00
Android Tablet*	Lenovo	1	$182.00
ESTIMATED TESTING COST – YEAR ONE			$3,013.00

* Price includes protective case and screen cover

6.6.6 Status of Systems

Due to barriers encountered around continual system usage and adoption, all four of the systems currently require updates or support to be fully functional. The class maintains contact with each of the communities through monthly WhatsApp calls to address questions from them and to get feedback for improving the systems.

6.7 Discussion

(Mac Mahon and Gill, 2018) identified that a major constraint to novel water treatment system implementation is not the physical implementation but the medium- to long-term support of such systems. Currently the treatment systems installed in the DR are not being used, which prevents us from evaluating the benefits of communication and long-term support of the systems based on the class structure. However, these results do indicate that even with access to a long-term support network for the system through points of contact within the service-learning class structure, the communities did not reach out to the class for operational or maintenance support. This suggests that these systems suffer from a lack of "boots on the ground" through the initial adoption stages.

Members of the class travel for one week each year to accomplish the large number of tasks required to achieve a holistic system installation. Though communication with communities occurs outside of this trip, one week per year of face-to-face contact appears to be insufficient to promote system use. Unfortunately, finding a person or organization that would be able to provide support for these system, as well as finding the funds needed to support this resource, is difficult, especially for communities in remote locations (Mac Mahon and Gill, 2018). Further, more information would be needed to inform how long these partners would need to remain in-country for system support or exactly what their role would need to be to promote long-term sustainability of the systems.

It is important to obtain information from communities to validate the idea that 'boots on the ground' would be beneficial, because it is not well-established how communities would want to progress in order to achieve full transfer of system control to the schools. This information is crucial to collect as few studies follow-up on water treatment interventions for periods longer than 12 months, with the majority that do concluding the utilized system was not an effective long-term intervention, and thus not considered sustainable (Clasen et al., 2015). Beyond this, site-specific barriers that contributed to the lack of system adoption and usage in this study have been identified.

6.7.1 Technical Barriers

As mentioned in past studies, community-scale water systems need to be effective, low-cost, easy to use, and sustainable (Lantagne et al., 2006; McGuigan et al., 2012; Schulz and Okun, 1983). Though the technologies used in this work are well-established, effective technologies, one of the barriers to system usage has been proving this effectiveness to consumers within the communities.

The schools wanted water quality testing to be conducted by local water authorities, not just a trained system operator, and for the water quality from the system to be certified by a local organization indicating that the water was safe to consume. Unfortunately, this type of testing and certification is not available through an established program in the DR.

Further, the school structure introduced technical barriers. As a service-learning course, travel for system installation is based on the university-based school schedule in coordination with the primary schools where the systems were installed. Based on these constraints, most class trips have occurred in May, resulting in system installation followed by the schools going on summer recess the following week. This resulted in the systems sitting stagnant until the beginning of the subsequent school year in the DR, and stagnation often leads microbial regrowth within the system (Coelho et al., 2003), and consequently adverse odor, taste, and smell (Mallevialle and Suffet, 1987). Studies have shown that a consistent supply of water within a system results in microbially safer effluent than an intermittent water supply (Lee and Schwab, 2005).

There were also supply-chain barriers to obtaining the parts needed to construct and maintain the systems. In particular, some of the UV systems that were installed were only available across the country, and the Zimba chlorination systems are only manufactured in small batches in India so replacement parts were hard to obtain.

6.7.2 Economic Barriers

Economic barriers have prevented system maintenance, which is a major cause of community-scale system failure (Varghese, 2004). Financially, system operation and maintenance rely on incentives for an individual to take care of the system and financial support to conduct the maintenance (i.e., travel to sites, testing materials, replacement parts, etc.), but installing the systems at schools introduced unforeseen constraints on the economics of the system. First and foremost, these systems were installed on the grounds of public schools that are funded by the Dominican Republic government, introducing rules and regulations regarding the way the system could be supported economically. In 2019, it was learned that schools are prohibited from any activity that produces income in the Dominican Republic. So even though community members typically pay for water and treatment, the schools could not sell the water to the community to generate revenue for system operation and maintenance costs.

The schools each have a small budget to purchase water, but use of these funds to support the water treatment systems does not provide incentive for the school to produce water for the wider community. Having the system, and not needing money to purchase water, could also hinder the school's ability to receive these funds long term, which would leave them with no way to maintain the system. Previous studies have indicated that lack of ability to afford, repair or replace technology leads to lack of behavior change and thus adoption (Parker Fiebelkorn et al., 2012a). Therefore, more collaboration with local government is need within the project to promote a sustainable economic structure surrounding the system.

Certification of the water quality from the systems (introduced above in technical barriers) would also require frequent, long-term testing of the water by a local water authority, outside of the testing that was set up to be conducted by the system operator. Even if a program was established to do so, travel to the water treatment system locations and testing costs introduce economic barriers on a system that currently lacks a funding mechanism.

6.7.3 Social Barriers

The ultimate goal of the systems was to provide safe water for an entire community, therefore many of the evaluation methods set up in this course were designed to measure community outcomes. Unfortunately, without ever getting the systems fully functional at the school level, and due to economic barriers, they did not expand to provide water to the surrounding communities. Considering the school and community as separate sample groups for evaluations of water preferences and the impact of the water system will be implemented in future work as the school and community, though associated, have different needs and wants with the system.

The location of the system within the community also created ownership and usage constraints. The community's access to the water was confined by the school's decisions around system operation and maintenance as the owners. This was compounded by constraints surrounding the school schedule, where public access to the school outside of school hours and breaks was not allowed for safety reasons.

Finding a local individual or group of individuals willing to assume responsibility for operating and maintaining the system also led to social barriers. In this study, school administrators and board members expressed concerns about the knowledge level of the individual who would operate the system. They wanted the individual to have experience with water treatment beyond the training they would receive from the class, but they did not identify who this individual might be. Operator turnover was also an issue because operators can change or move out of the area unexpectedly, resulting in a loss of knowledge of the system(s).

6.8 Conclusion

The integration of all these constraints is complicated and uniquely specific to the given environment in which each water system is installed. Though a service-learning model can help provide continued support for the longevity of a project, the ability for the model and this support to improve community-scale system adoption could not be assessed due to these other barriers that prevented water system usage. These other barriers have been categorized as technical, economic, and social, and provided insight into the experience installing community-scale water treatment systems as a university-level service learning course for informing future international development projects.

The class is working to overcome many of the barriers experienced throughout this project, but believe the financial and operational constraints specific to selection of schools as the site for the systems must be overcome to achieve full-time system operation and sustainability. Formal evaluation of these dynamics as well as of public perception of the water treatment systems and its acceptability will be conducted in future work.

CHAPTER 7. LESSONS FROM THE IMPLEMENTATION OF SCHOOL-MANAGED DRINKING WATER TREATMENT TECHNOLOGIES IN USAIN GISHU COUNTY, KENYA

7.1 Abstract

Low-cost household water treatment systems have been studied extensively to address the global gaps in access to safe drinking water, but they are met with many barriers to adoption, including the effects of treatment on the taste and odor of the finished water. Beyond the barriers faced by treatment technologies, water sources that are consumed outside of the home are often overlooked. Yet those individuals who go to work or school can spend a large fraction of their day away from home, where safe water is also needed. This is especially important for school children in Kenya, where students can spend all of their time away from home because primary boarding schools are popular. In this study, we aimed install drinking water disinfection systems at primary schools in western Kenya to evaluate the difference in adoption of ultraviolet water treatment versus traditional chlorination methods. Due to unforeseen circumstances, we were unable to evaluate this dynamic, but instead we discuss the project parameters and evaluation methods that would have been beneficial to the informing the outcome of this project. These include detailed site evaluation before project installation, community involvement in design, and a thorough understanding of qualitative and quantitative data collection methods.

7.2 Introduction

Access to clean, safe drinking water is recognized as a basic human right, yet it is estimated that 785 million people globally still lack access to basic water services. There have been many recommendations for point-of-use (POU) home water treatment and safe storage (HWTS) to overcome this gap in access to treated drinking water in resource deprived settings (Freeman et al., 2009; Kotlarz et al., 2009), yet only 45 percent of households in Kenya use appropriate water treatment methods. 24% of homes boil their water and 22% add bleach/chlorine, whereas 54% of households consume untreated water (KNBS, 2014). Further, it has been shown that high rates of microbial contamination have been found after POU treatment in Kenya (Grady et al., 2015). In 2019, the number of Kenyans served by regulated water services was reported at 57% (WASREB, 2019), but this still leaves a significant gap in the number of alternative treatment methods that are needed throughout the country.

Drinking water away from place of residence is also common in Kenya, making it difficult for HWTS technologies to improve all of the drinking water consumed by individuals throughout the day. According to (Onyango-Ouma and Gerba, 2011), in rural western Kenya, both schoolchildren and adults spent most of the day outside of the home while only returning home in the evenings. In their study, 80% of respondents in these groups identified that they drink water outside of the home. The main sources of the drinking water consumed outside of the home were rivers (31%), boreholes (14%) springs (4%) or wells (4%). Further, 63% of respondents did not know whether the water they were consuming outside of the home had been treated, and an additional 25% were sure the water was untreated. Ultimately, consuming water outside of the home is a necessity for this population based on required daily activities, and in interviews, respondents identified accessibility as the single most important factor in choosing a water source under these circumstances (Onyango-Ouma and Gerba, 2011). In this work, we discuss the installation of 4 water treatment systems at primary schools in western Kenya that were designed around the schools' existing drinking water taps in order to make the water accessible and reduce the need for students to change their current habits around drinking water.

To inform the adoption of these systems, we wanted to evaluate the impact of taste on the usage and maintenance of the installed systems. The taste of treated water that has been disinfected with chlorine (Diergaardt and Lemmer, 1995) and negative associations made with this chemical taste (Waddington et al., 2009) have negatively impacted the adoption of drinking water treatment systems. In this study we aimed to compare ultraviolet (UV) water disinfection with chlorine disinfection with the hypothesis that UV disinfection would be more widely accepted because the taste of the treated water does not change. Due to unforeseen project changes, including the refusal of systems utilizing chlorine, we were unable to evaluate this hypothesis, so herein we retrospectively assess the research methods that would have been beneficial for promoting success within this project *(presented in italicized text)* and similar projects that attempt to use technical or engineering solutions to address a grand challenges. The goal to improve the use of interdisciplinary methods in international development projects is supported by the United Nations, which reports the need to bring together data from different communities and utilize innovation tools to achieve the 2030 SDG agenda (United Nations, 2018).

7.3 System Design and Installation

Taste and odor have been identified as reasons individuals and communities have an aversion to drinking water that has been treated with chlorine (Crider et al., 2018b), even though it is well understood that chlorine is a low-cost, effective way to disinfect water and reduce diarrhea in developing countries (Arnold and Colford, 2007). It is also considered a scaled-up technology in Kenya, where it is branded as WaterGuard (Christensen et al., 2015). Ultraviolet (UV) water disinfection has been proposed as a way to overcome this barrier. Therefore, our initial study aimed 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 the treatment systems can help overcome issues with adoption.

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. They are also a location that is consistently occupied and managed by the same group of people, which we hoped would allow for consistency in system operation. Further, children can be agents-of-change for improved health communication in the home (Mwanga et al., 2008; Onyango-Ouma et al., 2005). Mothers have reported high levels of trust in the health information relayed by their children from school (Bresee et al., 2016), and children can also be involved in household responsibilities such as taking care of their younger siblings, which can contribute to household behavior change (Olayiwole et al., 2003). The specific schools were selected as study sites based on the following criteria. The schools needed:

- to be within walking distance of each other to allow for centralized system operation and maintenance;
- to have no current water treatment method for the water they consume;
- and to 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 systems were designed to consist slow sand filters (SSFs) in series, followed by water disinfection with storage before UV treatment but after chlorination.

7.3.1 Slow Sand Filter

Each system was designed to use a series of slow-sand filters for preliminary treatment of the water. These filters were designed to remove particles and dissolved organic chemicals for the source water to produce effluent water with turbidity below 1.0 NTU. These SSF utilize a porous plastic plate enclosed in a mesh bag, as opposed to gravel, in the water collection zone at the bottom of the filter. This change allows for easy maintenance within the filters because there is only one medium that can be removed and rinsed when the filter becomes clogged. The porous plastic plates were brought with our team to Kenya, and the sand and plastic filter barrels were obtained in country. Figure 7.1 is a picture of the series of filters that was installed at our first school (school A). The series of filters utilized a basic float mechanisms to control the amount of water that was allowed into the first filter, removing the need for user interaction with the system, unless the filters were clogged.

Figure 7.1. Initial installation of a series of slow-sand filters installed behind one of the classroom buildings at school A.

7.3.2 UV Treatment System

The UV reactors for these systems were powered by a 30 W solar panel wired to a charge controller (10 amp), with output to both a standard car battery (30 amp hours) for energy storage and directly to the UV reactor for power. The UV reactors used were low-pressure (LP) lamp reactors designed to operate at 2 gpm (7.5 lpm) at 95% UV transmittance at 254 nm (UVT_{254}). At this flow rate, they provide a UVT_{254} dose that meets the United States public health standard of 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. 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), and therefore available on-demand (Barstow et al., 2014), because there is no residual disinfectant in the water with this treatment method, and therefore stored water can be contaminated post-treatment during storage (Reygadas et al., 2015).

7.3.3 Automatic Chlorination

The automatic chlorination system, Zimba (http://zimbawater.com/), was used for water chlorination. The system is a sequencing batch reactor, with no moving parts, that can operate in a continuous-flow system. Water flows into the top reservoir of the system, where a Mariotte Jar setup is utilized to appropriately dose chlorine. As the water rises above the cup where the chlorine is being dosed, the water and chlorine mix, and a siphon releases the mixed solution into the bottom reservoir of the Zimba, which is fitted with a tap. In this setup, the tap dispenses water into a storage tank and the system will run batches in a continuous manner. This system has been shown to consistently dose chlorine within the WHO recommended dose of 0.2-2 mg/L (Amin et al., 2016). After chlorination, water was stored in a holding tank with a tap for use and consumption.

7.3.4 Final Installation Details

Community engagement and approval have been highlighted as crucial factors in the successful implementation of water treatment interventions (L.W. Gill and Price, 2010), so after the schools were selected, we had discussions with each of them to talk about the water treatment system we wanted to install at their school, and allow them to ask questions. After these discussions, each school accepted the treatment plans we proposed, and a basic schematic of the initial design is illustrated in Figure 7.2.

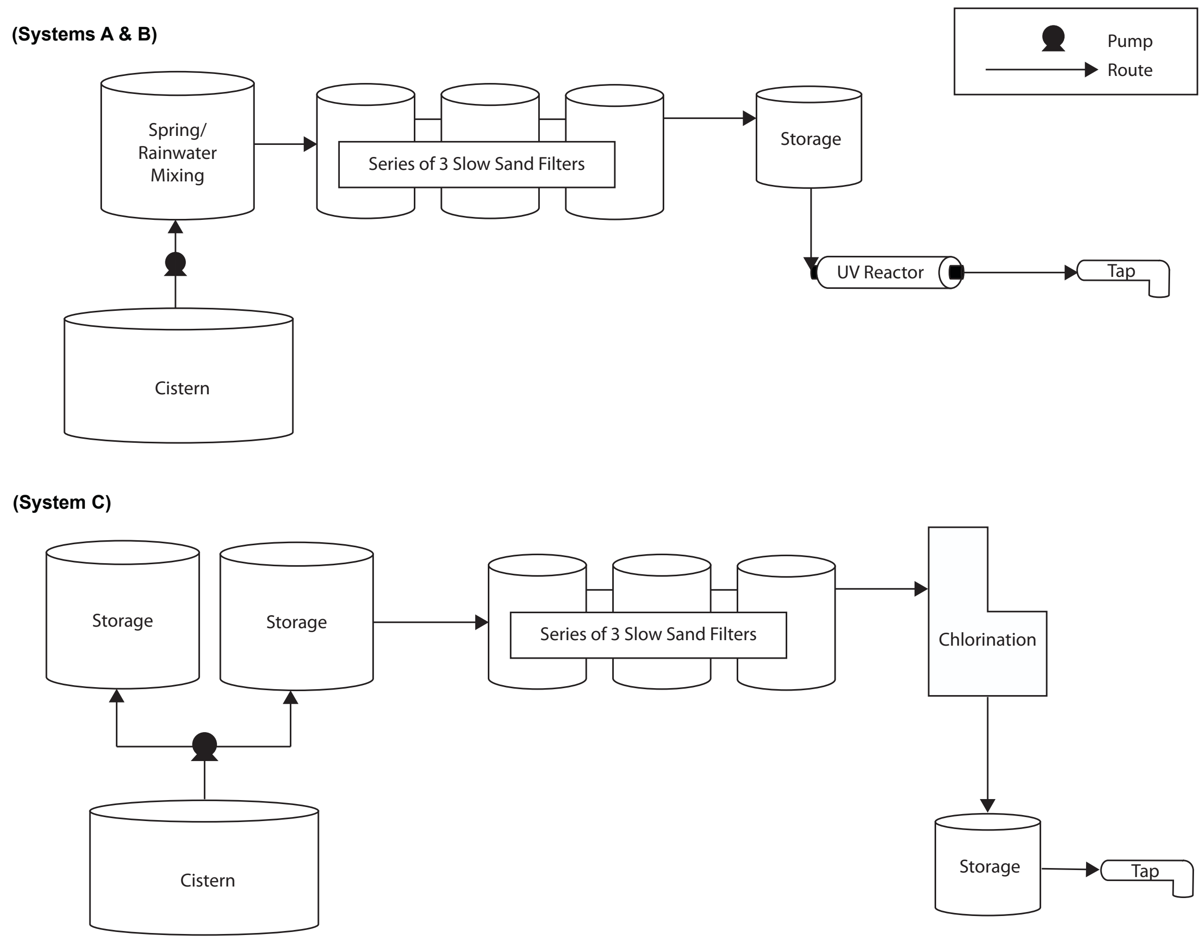

Figure 7.2. Basic design schematics for the water treatment systems proposed and agreed to at schools A and B, which utilized UV disinfection, and school C which was designed to utilize chlorine.

The chlorination system was the third system to be installed, after two UV systems at schools A and B, and before we began installation, the school asked to have a discussion. They conveyed that they would not use a system that chlorinated the water for consumption purposes, further claiming they would only use it for cleaning. They informed our team that chlorine would change the taste of their food, water and tea, and said they knew the neighboring schools had received UV systems which would not change the taste of their water. With this new information, they said they would like a UV water treatment system or no system at all for the water they consume. Therefore, arrangements were made to get another UV system, and an additional school was contacted for installation of the automatic chlorination system. This school (school D) was not neighboring the first three schools, and they already utilized chlorine for water disinfection.

This is a conversation that should have been appropriately recorded for further analysis, as should all of the conversations had in the field. In many international development projects that focus on engineering components, a priority is placed on quantitative data collection and ensuring the proper function of the intervention. This is especially true, understandably, when the intervention impacts human health, as is the case with water treatment. But too often, simple data collection methods like observations, informal interviews, and recording accurate field notes are neglected. But observational research and the use of informal interviews have been used in many mixed-methods studies to inform the context around an intervention (Caruso et al., 2014; Morinville, 2017; Rosenberg et al., 2008). They are also productive tools to use when there are few other ways to collect data about a subject group (Connolly, 1990), which we believe would have been the case in this study. Individuals at the schools were engaged in work when we spoke with them, so this strategy would have made more effective use of both their time and our time, by providing crucial context to inform future, formal data collection methods that could inform perceptions around chlorinated water. Therefore, it is important for researchers in the natural science domain to be properly trained in methods of appropriate qualitative data collection when these conversations occur.

7.3.5 UV Treatment Systems (Schools A, B, and C)

The source water entering systems A, B and C was a blend of spring water and rainwater. The ratios of each are undefined and variable as they differ throughout the year based on rainfall. When the systems were operated in the rainy season, all of the source water tested negative for *E. coli* using Compartment Bag Tests (CBTs) (Aquagenx). This presented a barrier in that we were unable to quantify inactivation of *E. coli* from the system disinfection; however, on a follow-up trip in the dry season, the source water tested positive for *E. coli*.

Therefore, if we were to improve the study design, we would have allowed for a period of water testing before systems were installed to inform both system design and time of year in which the system should be installed to be able to properly check for system function.

After installing the series of SSFs at school A, there was not enough water flow to support the water demand at school A, so we changed the filter design to a larger, standard sand filter that drained into a storage cistern (Figure 7.3). Schools A & B share a storage cistern, and school C has their own. The use of spring water and rainwater as the source water allowed for this design change from SSF to standard sand filter.

Figure 7.3. Standard sand filter that was installed after the source water (spring) and before a storage cistern from which water is pumped to schools A and B. School C received their own filter of the same design

An updated schematic of the new systems with these changes is presented in Figure 7.4.

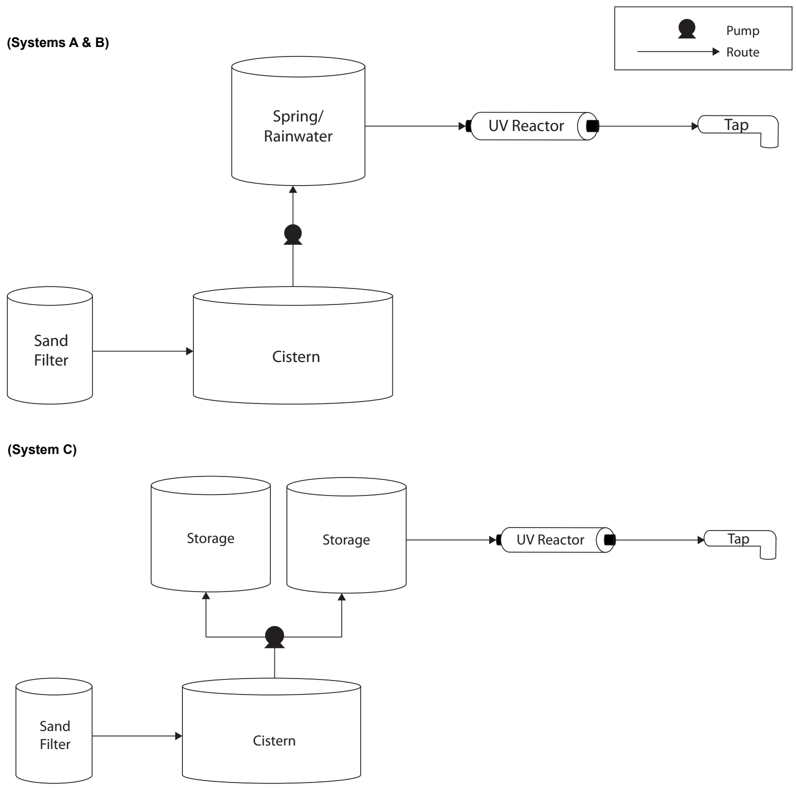

Figure 7.4. Basic design schematics for the water treatment systems after the changes were made to adapt the study to 3 systems utilizing UV treatment (schools A, B, and C)

> *With these project changes, we should have also evaluated how past projects that had been conducted in this location had an impact on the schools, and how these issues we encountered in our installation might influence our project design or affect the outcome of the project as a result. School A had previously had a pump followed by a series of three hollow membrane filters installed before their water taps. When we arrived, it was not in use, and a reason for this was the cost of replacement filters. Gez (2021) highlights the need to listen to local voices in development work, because project timelines and recipient community timelines (where the recipient is influenced by an intervention even when the project is over for the donor) differ. This leads to different experiences by each involved party with different impact and outcomes (Crabtree, 2013), which can influence community reaction to future projects done in the area (Gez, 2021). Previous project failure, combined with our reaction to handling issues within this project, might influence community adoption, and these dynamics should have been evaluated.*

A plumber from the community was employed to plumb all of the systems, and a welder built solar panel roof brackets and boxes to contain the systems and prevent tampering (Figure 7.5). The box to contain the system was designed with a window to allow the operator to easily check whether the system was on or off.

Figure 7.5. System components that were designed and constructed by the welder; (a) a solar panel bracket to hold the panel in place on the roof and locks so the panel cannot be stolen, and (b) a box to protect the system from tampering.

A local mason was used to build a structure for the system at school B because the tap was in an open field with no protection, and there would have been no protection for the system. The front panel was designed to have small windows, again so that the operator would be able to easily check the system operating lights (Figure 7.6).

Figure 7.6. Structure built by a local mason to support and protect the water treatment system at school B because their tap was free-standing in an open field.

All of the UV system components are currently functional, but they are not being used consistently. There was initially a problem with surges of energy from the charge controller that would burn out the system lamps. A surge protector was installed, but the surges seemed to be frequent, and required that someone continuously check to make sure the system is operating, which while we were there, was not taking place. Further, school C completely removed the sand from their sand filter because they said that it was clogged.

> *Technical component testing is another area that we would improve in future project design. The surge protectors were sourced from the US, and we had issues with multiple other system components while in country that could have been overcome by gathering and thoroughly testing the local components for the system prior to system installation. We had issues with multiple charge controllers (both locally sourced and sourced in the US), and could not find appropriate wire connectors (which led to many issues with poor or loose system connections), both leading to project delays.*

7.3.6 Chlorine Treatment System (School D)

A fourth school was selected for installation of the chlorination system (system D). It was constructed to be able to use groundwater that the school had from a well. This well was not deep enough, leading to extremely turbid water.

The system was designed to peddle pump water from the well into a coagulation/flocculation tank when the valve from this tank to the rest of the system was closed. In this tank they were to add 1 tsp of alum, stir, and allow the water to settle. The visual difference in turbidity can be seen in Figure 7.7.

Figure 7.7. Water from the well at school D before (right) and after (left) treatment with alum.

The coagulation/flocculation tank connected to the rest of the system from a pipe on the side of the tank, about 2” from the bottom of the tank (above the settling height). After the settling time, the valve could be opened, and the system would treat the water (SSF followed by batch chlorination with the Zimba) without any other operator involvement. Then water was stored for use. A tap was installed lower on the tank so that once empty of water, the valve to the rest of the system could be closed, additional water could be added to the tank, and the waste could be drained.

School D disassembled their system after our initial installation, and on a follow-up trip they said there were issues with students tampering with the system, and that they wanted to start collecting rainwater for the system. Our team installed a rainwater collection system that could be used to bypass the coagulation/flocculation tank when rainwater was available, and the final system design schematic is presented in Figure 7.8. On a follow-up trip after this installation, the system was again disassembled, and the school director opened discussions with our team about their dislike of chlorine and their need for a solar pump to operate the system.

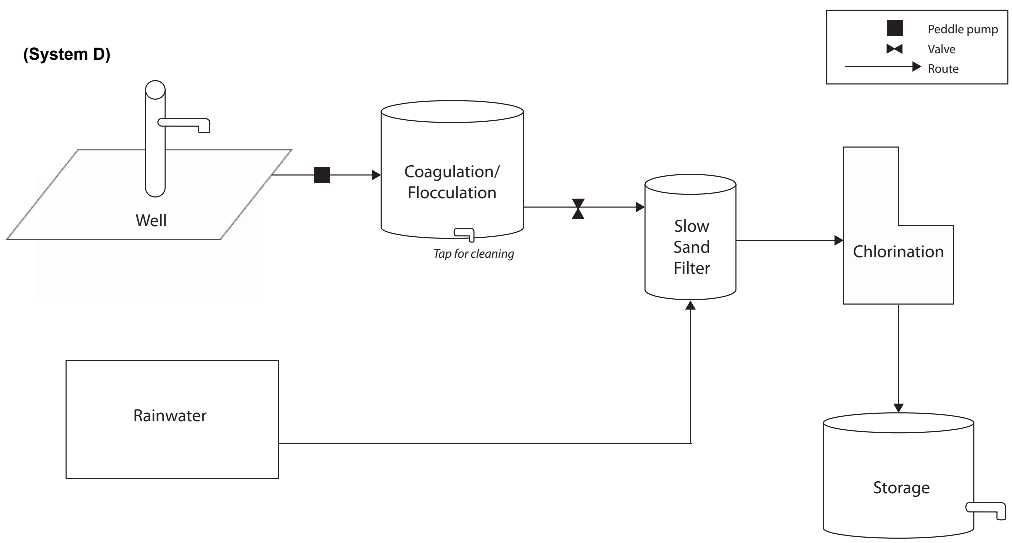

Figure 7.8. Basic design schematics for the final design of the water treatment system installed at school D.

The frequent disassembly of the system at School D was a result of a few issues that should be improved for future projects. First, systems should require minimal work from the recipient for operation and maintenance. There were multiple issues with the durability and reliability of the Zimba system, as it needed to be perfectly level to operate properly, which was difficult in a rural school setting with minimal resources, and the siphon in the Zimba also needed to be reprimed after about 2 weeks of non-use. This would then be followed by the need to re-level the system, which as mentioned, was difficult even during initial installation. The SSF produced water that was visibly more cloudy than the water entering the filter, as well. This was the case even after new sand was purchased, sifted, washed, and added to the filter. This echoes the conclusions of multiple studies in this space, that systems should be easy to operate and maintain (García-Ávila et al., 2021; Guchi, 2015b). *Further, the school lacked a consistent water source, which we argue is crucial to* *project success. With frequent changes to what water is available for the system, the needs of the system, the work required of the school, and the training required for system operation and maintenance change.*

The systems were designed to be as easy as possible to operate. For the UV systems, the operator just needed to flip the system switch on in the morning, and make sure the green light on the UV reactor was illuminated. For the chlorine systems, the operator just needed to check once a week to make sure that there was chlorine still in the Zimba. Details about the system testing methods are provided in the SI file.

7.4 Surveys

Surveys were developed to gain a basic understanding of the user acceptance of the systems. The surveys were intended to be conducted pre- and post-installation with a follow-up survey after 6 months of system use. Surveys were developed for students at each school and the employees. The survey methods were approved by IREC at Moi University (#0001880) and the Internal Review Board (IRB) at Purdue University (#1801020094). Unfortunately, the timeline for IRB approval exceeded 8 months, and therefore, pre- and post-surveys were unable to be conducted. The surveys were modified to be follow-up surveys only, and were conducted about 2.5 years after initial system installation. It is unclear how much the systems were used during this time because the location of the systems directly before the existing taps at Schools A, B, and C ensured that water ran through the treatment mechanisms, but did not ensure that the UV disinfection systems were operating properly.

Surveys were provided to each school in paper form, in manila envelopes. The head teacher at each school was given instructions on administering the surveys. They were asked to read the children an assent form, and pass out the surveys. Once completed they were to collect the surveys, and seal them in the manila envelope. Each school had about a week to complete the surveys before they were collected. Students were provided with questions that have two answer options, with only one open-ended question. These questions were designed to compare the taste preferences and trust students had related to their water at home and the water at the school. Questions were presented in both English and Swahili.

School employees, including teachers, administrators, and non-teaching school employees, were given a different set of survey questions. Employee surveys reflected the same set of questions that they students were asked, with an additional section to collect their opinions on the installed water treatment system. These additional questions were aimed to evaluate the perception of long-term system usage and maintenance through open-ended questions. They also addressed whether the employees believed schools would be willing to pay for one of these systems, and if so, how much they think the system should cost.

Summary statistics were used to summarize these data. Table 7.1 summarizes the survey responses from students at each school, where N = 184, 38, 61, 114 at schools A, B, C, and D, respectively. Most students indicated that they liked the taste of the water at both school and home, for schools A, B, and C this majority was >90%. At school D, most students get their water from boreholes at home, and they responded that they like the taste of their water at a lower percentage (77.1%) than at the other schools. They also responded that they believed their water at home would not make them sick at the lowest rate of the three schools (78.7%). Of the students that said they did not like the drinking water at their home, their water sources were boreholes, rivers, streams, or other.

Table 7.1. Summary statistics of student responses to survey questions after the water treatment systems had been installed.

	School A	School B	School C	School D
What is your gender?				
Male	51.6%	92.1%	49.6%	42.6%
Female	48.4%	7.9%	50.4%	57.4%
Do you drink the water at the school?				
No	0.5%	5.3%	0.9%	0.0%
Yes	99.5%	94.7%	99.1%	100.0%
Do you like the taste of water at school?				
No	6.0%	5.3%	7.9%	1.6%
Yes	94.0%	94.7%	92.1%	98.4%
Do you think the water at school will make you sick?				
No	93.4%	94.7%	92.1%	98.3%
Yes	6.6%	5.3%	7.9%	1.7%
Where do you get the water you drink at home?				
Borehole	29.9%	10.5%	34.2%	68.9%
Buy	0.5%	0.0%	0.0%	0.0%
Dam	3.3%	0.0%	0.9%	1.6%

Table 7.1 continued

Rainwater	2.7%	0.0%	1.8%	1.6%
River	40.8%	21.1%	49.1%	3.3%
Spring	1.1%	0.0%	0.0%	19.7%
Stream	5.4%	0.0%	0.0%	0.0%
Tank	6.0%	15.8%	3.5%	0.0%
Tap	1.6%	50.0%	7.0%	1.6%
Other	8.7%	2.6%	3.5%	3.3%
Do you like the taste of water at home?				
No	6.0%	2.6%	0.9%	23.0%
Yes	94.0%	97.4%	99.1%	77.1%
Do you think the water at home will make you sick?				
No	94.0%	97.3%	100.0%	78.7%
Yes	6.0%	2.7%	0.0%	21.3%
Think about the taste of water. Does it taste better at school or better at home?				
About the same	65.8%	68.4%	62.0%	61.7%
Home	18.5%	29.0%	36.3%	5.0%
School	15.8%	2.6%	1.8%	33.3%

One of the biggest flaws in the survey methods was that we believe students might have been given answers to surveys. The open-ended responses to the question ‘Is there anything else you would like to share with our team?’ solicitated verbatim responses within certain classes. For example, from school D, class 5 all responded “Make sure the system is working; wahakiki she maradi huo unaganga kazi vyema; maji ni uahi”, and all of class 6 responded with some version of “I like drinking clean water to keep my body healthy, your project is the best”. At school B, all of class 8 responded with some form of “the water has worms”, and 4 out of 7 respondents from class 6 said they want or need water in school, whereas the other 3 students did not respond.

Table 7.2 summarizes the survey results from school employees, where N = 14, 9, and 8 for schools A, C, and D respectively. Surveys from school B were not included because many of the surveys appeared to have been filled out in the exact same way, with what appeared to be the same handwriting, and we got more responses than there were school employees.

Table 7.2. Summary statistics of school employee responses to survey questions after the water treatment systems had been installed. School B data has been omitted due to inconsistencies between the number of school employees and the number of surveys that were answered.

	School A	School C	School D
What is your gender?			
Male	35.70%	88.90%	87.50%
Female	64.30%	11.10%	12.50%
Do you drink the water from the new treatment system at the school?			
No	0.00%	11.10%	12.50%
Yes	100.00%	88.90%	87.50%
Do you like the taste of water at school?			
No	0.00%	0.00%	12.50%
Yes	100.00%	100.00%	87.50%
Where do you get the water you drink at home?			
*Borehole**	64.30%	22.20%	75.00%
Rainwater	14.30%	11.10%	0.00%
River/Stream	21.40%	44.40%	0.00%
Tap	0.00%	11.10%	0.00%
Multiple Sources	0.00%	11.10%	0.00%
Do you like the taste of water at home?			
No	14.30%	11.10%	37.50%
Yes	85.70%	88.90%	62.50%
Do you think the water at home will make you sick?			
No	78.60%	88.90%	50.00%
Yes	21.40%	11.10%	50.00%
Think about the taste of water. Does it taste better at school or better at home?			
About the same	64.30%	77.80%	37.50%
Home	0.00%	22.20%	0.00%
School	35.70%	0.00%	62.50%
Has maintaining the new treatment system required you to do any additional work that you were not doing before the system was installed?			
No	92.90%	77.80%	75.00%
Yes	7.10%	0.00%	12.50%
Has there been any problem with the new treatment system since its installation?			
No	64.30%	44.40%	87.50%
Yes	35.70%	11.10%	12.50%
Other	0.00%	33.30%	0.00%
In your opinion, do you think the school will maintain this treatment system over time into the future?			
Did not answer	0.00%	11.10%	0.00%
No	0.00%	11.10%	0.00%
Yes	100.00%	66.70%	87.50%
Do you think other schools would pay for a treatment system like this?			
No	35.70%	33.30%	87.50%
Yes	64.30%	55.60%	12.50%

*Borehole includes the responses boreholes, wells, and underground

We see similar trends in water preference in this data compared to that of the students, where school D employees use water from boreholes at home at the high-test percentage (75%), and also like the taste of their water at home at the lowest percentage (62.5%).

For questions regarding the installed water treatment system, of the respondents that answered no to whether or not the schools should be responsible for purchasing and maintaining water systems, one responded that the director should be responsible, three responded that it is the government's responsibility, and one respondent said it was the donor's responsibility. We believe that the responsibility for who should be in charge of providing water to the schools could be a main barrier to system adoption, but could make this conclusion based on these surveys.

The study needed to be able to adapt when the data collected did not actually inform the hypothesis. In general, we are only able to make rudimentary observations from the survey data collected without pre- and post- surveys to understand changes in individual perspectives around water preferences and how they might have changed after system installation. By only conducting the initial survey as a follow-up survey, we were unable to inform whether or not the schools preferred UV treatment over chlorine. The surveys should have been more rigorously designed from the onset, as well as adapted when the pre- and post-surveys were not conducted.

7.5 Discussion of Areas for Project Improvement

7.5.1 Timelines

Ultimately, this project experienced a lot of unforeseen circumstances that required the team to adapt in real-time to changes in project design. Therefore, in hindsight, we believe that one of the most important changes this project would have benefitted from was alternative management of the project timeline. Timeline is crucial for coordinating projects between multiple stakeholders and for accounting for flexibility within a project. The timeline for this project was a four-month trip to meet with communities, conduct final system design, and install systems, with three follow-up trips to address project issues and collect survey data. As mentioned, changing this timeline to allow for more up-front, in-country data collection would have allowed us to collect initial water quality data that could have informed better timing on system installation, but the study timeline also did not account for assessment of local technologies and tools that would be used in the systems, and their influence on design. It would have also allowed for us to collect and thoroughly test local system components for ease of installation.

The conversations with schools C and D related to their dislike of chlorine would have been beneficial to have at the beginning of the project. Instead of presenting the schools with one disinfection option for their system, we could have led valuable up-front discussions about system options. This would have also allowed for the inclusion of participatory design, or co-design into the water treatment systems. Co-design has been used extensively in the business context, but mostly as early stage co-design used to inform individual user's perceptions on technology. But lessons for this context can be taken from Blake et al. (2014) who describe moving past early stage co-design, into community-based co-design which is required for action based research, and Ssozi-Mugarura et al. (2017) who implement this through a cyclical and iterative six-cycle method, with the use of interdisciplinary methods such as semi-structured interviews, workshops, and focus groups. Through their co-design process they found that insights into expectations, perceived roles, and community relationships emerged. These dynamics would have been useful to inform similar questions in this study such as who's responsibility it is to provide schools with safe water, and who the schools thought should take care of the new water treatment system.

To address these issues in future project design, we would propose a short, preliminary trip to the recipient communities, to obtain the local supplies that would be used in system design, and to begin design conversations with the communities. After which, a period of system testing and initial co-development conversations would occur while the team was not in country. This would be followed by the trip continue co-design with the new technical information, and to install the systems. These steps would have helped our team overcome issues with:

- system components or tools that were needed but not available in-country;
- assessing the function and pitfalls of different system components (including charge controllers, batteries, and UV reactor lamps);
- understanding testing and maintenance strategies that could be employed;
- and adapting to the intersecting dynamics of project boundaries and community needs.

We believe that this would be a crucial project component that was missing in this work and should be included in future design of international development projects.

7.5.2 What constitutes data and evidence?

We also recognized the real-time decision making and design that takes place in international development, and adapting research in this context requires detailed understanding of how to use interdisciplinary research methods. There were multiple scenarios in this work where the lack of sufficient knowledge surrounding how to effectively collect qualitative data or adapt qualitative data collection methods hindered the collection of critical information to inform decision making and the outcome of the study. This is not uncommon, as Lach (2014) highlights that defining appropriate methods for collecting data such as what actually constitutes usable data, how can this data be appropriately analyzed, and how do we define evidence, is a challenge faced in the interdisciplinary work space, especially between natural and social sciences.

To improve upon this, each member of our implementation team should have documented detailed field notes with emphasis on recording informal interviews, because important lessons were learned through the conversations we had with communities in the field. Working in this observational research domain would have also allowed us to collect important information on school's interactions with water and the system. For example, every time I saw a student get water for drinking during this work, they would wash their hand (if they were drinking from them) or their receptacle in the source water before collecting it to drink. Recording such data as a team would have allowed our team to collect a more complete picture of the project site and community as well as to inform more formal data collection methods for new topics that were uncovered.

7.5.3 Behavior Change Models

In this work, we also aimed to minimize the need for anyone to change student and school employee behaviors by installing the water treatment systems directly before existing taps that were already used for drinking water in the schools with UV treatment systems. By minimizing the need for behavior change for most of the school members, we aimed to influence student belief that consuming clean, safe water could be easy, and in turn influence this change at home through children as agents of change (Onyango-Ouma et al., 2005). But ultimately, behavior change played a role even when it was not associated with needing to operate the system or communicate the need for safe water. As identified by Dreibelbis et al. (2013), there are multiple dimensions of behavior change and levels within these complex problems that cannot simply be solved by employing one method of behavior change theory.

The systems in this study were designed so that the user could easily see the lights indicating that the system was working, but during our visits to the schools these lights were often off. Yet, the majority of school employees at school A indicated that the systems were operating properly (64.3%). Unfortunately, due to the change in survey methods of this study, we were unable to evaluate this before the system was installed, which limits what we can conclude from this result. But the knowledge of how to adapt the tools being used in the study would have impacted the ability to evaluate this project. Adopting a new technology usually requires some type of human behavior change, and the behavior change models that influence the adoption of point-of-use water treatment have been understudied (Parker Fiebelkorn et al., 2012b). Future work should consider these models and how they might help influence perceptions around the importance of changing behavior to consume safe drinking water.

7.5.4 Ethics

It is also important for researchers to consider the ethical implications of even minor interventions in development work. In this reflection, we want to highlight our experience with the ethics of installing the water systems in primary schools. The Kenyan education system uses a 8-4-4 model, where students attend primary school for 8 years, secondary school for 4 years, and university for 4 years. After grade 8 (the last year of primary school), students take a primary school exit exam to earn the Kenya Certificate of Primary Education (KCPE) (Lucas and Mbiti, 2012). These exams influence placement of students in secondary school, post-secondary school, and employment based on their scores (Kibet, 2013). Within this project, conversations (which as mentioned earlier should have been recorded as informal interviews) revealed that one of the motivations for schools to receive and maintain a water treatment system was that, as a private school, the school could attract higher level students, improve KCPE scores and increase the amount of government funding they receive as a school. Private schools charge fees and often cater to wealthier, more educated households (Lucas and Mbiti, 2012). Though we were working in schools that still needed access to safe water, we may have created even greater inequities between higher and lower performing students by potentially influencing the school's ability to attract students and receive government funding.

7.6 Conclusion

The design of the initial study changed significantly throughout the project, particularly during the system installation and follow-up process even though we tried to plan for changes and employ project guidelines previously reported to promote system success. We included the employment of local trade workers to install systems, we used locally supplied materials whenever possible, setting up a local maintenance structure, and had a trusted member of the communities, fluent in water treatment, as part of our team (Dacunto et al., 2015). But the failure of these systems to become fully integrated into the school's daily lives highlights the need for development projects to be adaptable and include interdisciplinary research and data collection methods to qualitatively and quantitatively assess the project through changes. Understanding proper methods for data collection in these times of flexibility can help inform intermediate steps between project installation and outcome.

Further, projects in international development operate in a real-time environment with complex dynamics that have the ability to impact every stage of the project. This often results in interventions that are only evaluated by success or failure (Gez, 2021), and much of the lessons learned and intermediate project steps and nuances are lost. To avoid losing critical data towards informing critical factors towards the success of WASH interventions, it is important to report experiences in this domain, both successful and unsuccessful, and reflect on the potential changes that could have improved the intermediate metrics that affect project outcomes we were able to obtain from this work. We propose that a preliminary trip to gather local materials for testing, assess the water sources to be used, and to build community relationships would have better informed system design. Thorough understanding of qualitative data collection methods and analysis would have better prepared our team to collect data informing system adoption and community preferences, and allowed for adaptation of methods throughout the project. We also emphasize the need to consider the ethics of decisions made throughout the project to reduce as many inequities as possible. Through this reflection, we emphasize how the integration of engineering solutions with interdisciplinary research methods, especially those from the social science domain, is crucial to collecting sufficient evidence to support decision making and outcomes throughout development projects.

CHAPTER 8. ALTERNATE APPLICATIONS OF AMBIENT UV FOR PATHOGEN INACTIVATION

8.1 Introduction

Applications of pathogen inactivation in water extend beyond drinking water in developing countries. Though direct applications of ambient solar UV radiation for water disinfection were not selected here for use at the community-scale, pathogens can occur and be inactivated by these mechanisms in naturally occurring or man-made bodies of water outdoors. Between 2007-08, 134 recreational water-associated outbreaks with at least 13,966 cases were reported, of which 40% were attributable to *Cryptosporidium* spp. (Hlavsa et al., 2011). *C. parvum* is of particular interest because the oocysts are largely unaffected by standard chlorination procedures applied in recreational waters for disinfection (Rochelle et al., 2002). The goal of this work was to simulate the potential for inactivation of *C. parvum* in an outdoor, Olympic-size swimming pool. It was hypothesized that *C. parvum* could be effectively inactivated in an outdoor pool, but the inactivation potential will decrease as a function of depth below the water surface.

8.2 Methods

Experiments were conducted to define the UVB/UVA action and effectiveness spectra for *C. parvum* oocysts (Busse et al., 2019). Effectiveness spectra were calculated as the product of the action spectrum and calculated (location and time-specific) spectral irradiance to identify the most effective wavelengths for inactivation; for the ambient solar spectra that were included in these calculations, peak inactivation effectiveness appeared at approximately 320 nm.

Raytracing software (Photopia, LTI Optics) was used to simulate the spatial distribution of ambient solar UV radiant energy in an outdoor Olympic size swimming pool (50 m x 25 m x 3 m). The walls of the pool were assumed to be 90% reflective at all wavelengths based on a standard material option in Photopia. The elevation angle of the sun was set to 70^{o}, relating to the approximate elevation of the sun in West Lafayette, IN during the month of July. The model is illustrated in Figure 8.1. As described in section 3.2.2, small-diameter, transparent spheres were included in the model as receptors to allow calculation of local fluence rate.

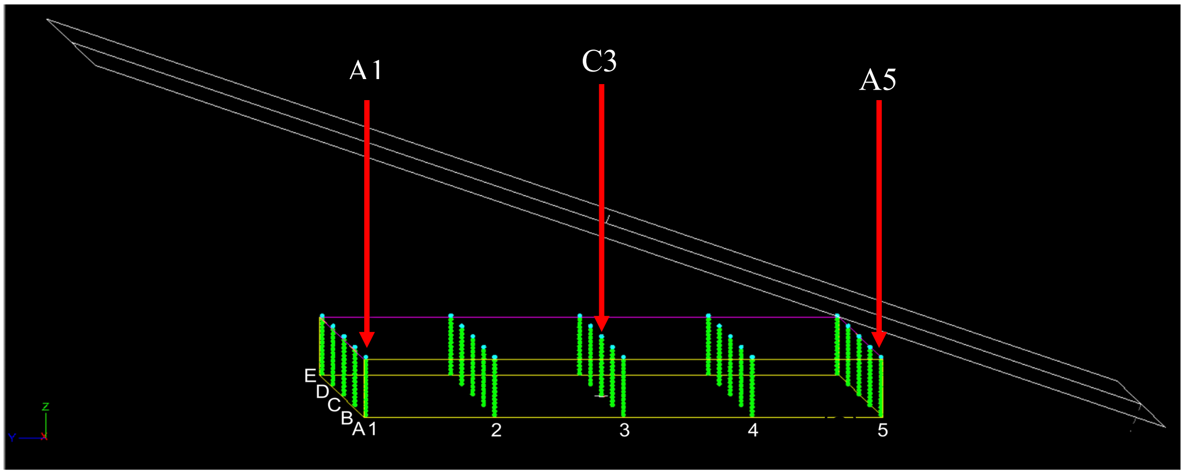

Figure 8.1. Simulation setup in Photopia (LTI Optics Inc.) for an Olympic size swimming pool exposed to ambient sunlight. Each green line, indicated by a letter-number combination is a series of 15 transparent spheres stacked with the centroids every 0.1 m depth. Positions along the width of the pool are indicated A-E, and positions along the length of the pool are indicated 1-5. The positions of the vertically stacked particles identified in this illustration (A1, C3, A5) are represented in the results.

The model provides an estimate of fluence rate imposed on each receptor sphere. This information was used to estimate the local fluence rate (W/m^2) based on the cross-sectional area of each particle. Particles were distributed evenly across the area of the pool and at 0.2 m incremental depths. "Test" particles were also placed 2 m above the surface of the pool, which is the same height at which the available UVB radiation is measured by instruments (Ultraviolet Multifilter Rotating Shadowband Radiometer) at the Purdue Agronomy Farm (USDA UVB Monitoring Network, West Lafayette, IN) and the height used in UVB modelling by the Tropospheric Ultraviolet and Visible Radiation Model (TUV) (National Center for Atmospheric Research). These test particles were used to make sure that the same amount of radiation that was leaving the sun model was reaching the surface of the pool in the model.

The transmittance properties of swimming pool water were measured from water samples collected in August and September of 2018 at three pools in Tippecanoe county – a personal swimming pool, a public pool, and an apartment complex pool. The highest and lowest transmittance conditions were represented by the public and personal pool respectively, and were thus used for simulations herein (Figure 8.2).

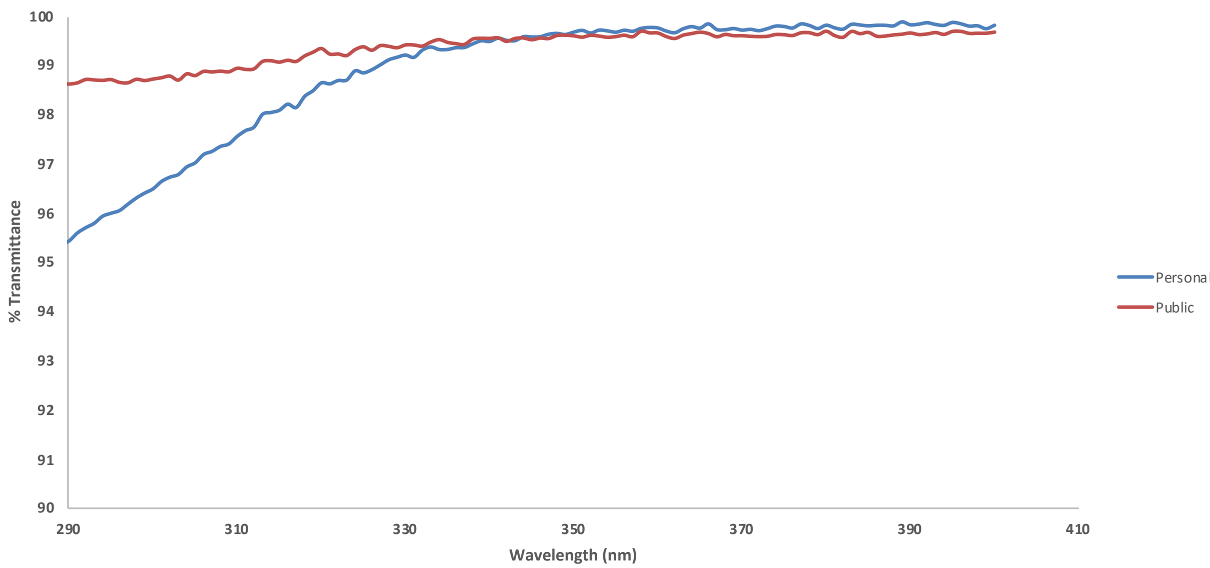

Figure 8.2. Transmittance of water in a public and personal swimming pool in West Lafayette collected in September 2018.

In the model, each ray's lumen value, when reflected, does not change, but when transmitted or refracted, the lumen value is diminished by the absorption coefficient (LTI Optics, 2014). Therefore, the absorption coefficient for the air:water boundary layer for the pool surface at each wavelength, with Fresnel reflections included, was calculated (Table 8.1).

Table 8.1. Transmittance of the water in the sampled public and personal swimming pools at the wavelengths of radiation measured by the USDA UVB monitoring network and the calculated absorption coefficient at the air:water interface used for the ray tracing model (reported in 1/in as these are the units required by the model).

	Personal Pool		Public Pool	
Wavelength (nm)	% Transmittance	Absorption Coefficient (1/in)	% Transmittance	Absorption Coefficient (1/in)
282	94.77	0.00872	98.64	0.03504
297	96.17	0.09927	98.64	0.03478
300	96.48	0.09102	98.72	0.03275
305	97.01	0.07713	98.79	0.03092
310	97.55	0.06308	98.94	0.02712
320	98.63	0.03496	99.34	0.01685
325	98.84	0.02974	99.37	0.01595
330	99.20	0.02045	99.41	0.01498

Fluence rate was calculated as radiant power per unit area imposed on an infinitesimally-small sphere (IUPAC, 1997), using the output watts from the Photopia model on small spherical receptors. Potential inactivation of *C. parvum* was then calculated based on the series-event model (Equation 8.1), where dose was the product of fluence rate calculated from the Photopia output at a given wavelength and location, and a set time of exposure.

$$\frac{N}{N_0} = exp(-kD) \sum_{i=0}^{n-1} \frac{(kD)^i}{i!} \quad \text{Equation 8.1}$$

Where,

N = concentration of viable organisms (cfu/mL)

N_0 = concentration of viable organisms prior to UV exposure (cfu/mL)

k = inactivation rate constant (cm^2/mJ)

D = dose of UV radiation (mJ/cm^2)

n = threshold number of damage events required for microbial inactivation

i = index.

k and n were wavelength-specific constants associated with the dose-response of *C. parvum* (Table 8.2).

Table 8.2. k and n constants for series-event model fit for *C. parvum* dose-response (Busse et al., 2019).

Wavelength (nm)	Inactivation Constant (k) (cm^2/mJ)	n
297	0.322	2
310	0.049	1
320	0.152	3
330	0.148	2

8.3 Results

One hour of exposure was chosen for inactivation calculations, and the general trend at every point can be represented by the two plots in Figure 8.3, where a depth of 0.0 m is the pool surface, and a depth of -3.0 m is the bottom pool surface. Figure 8.3a illustrates the trend for all of the points in the pool not shielded from radiation by the bottom pool wall due to the elevation angle of the sun (column 5 in Figure 8.1), and Figure 8.3b illustrates the trend for all of the particles in column 5.

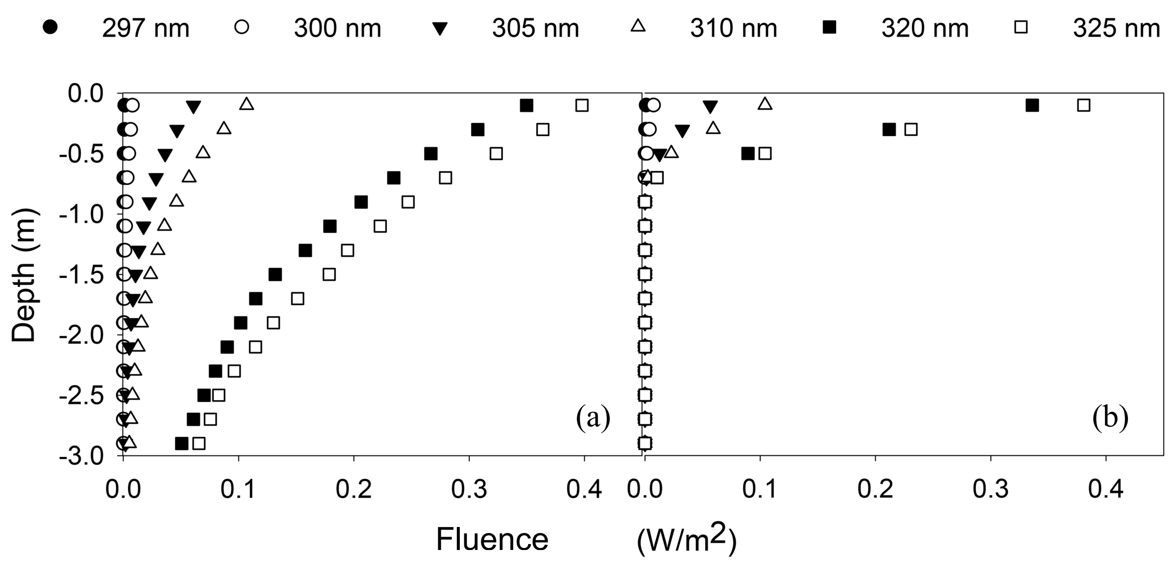

Figure 8.3. The fluence rate resulting from Photopia simulations is shown as a function of pool depth at 297 nm (●), 300 nm (○), 305 nm (▼), 310 nm (△), 320 nm (■), and 325 nm (□). Plot (a) shows this trend at pool positions where there is no wall impedance on the incoming irradiation (position C3) and (b) shows the trend at positions where the pool wall blocks some amount of ambient sunlight (position A5) (Busse et al., 2019).

The inactivation potential for the particles in the A1 position at 297 nm, 310 nm and 320 nm are provided in (Table 8.3). After one hour of exposure, these simulations indicated approximately 6-$\log_{10}$ units of inactivation just under the surface due to radiation at 320 nm. This value decreases significantly with increasing depth to only 0.28-$\log_{10}$ units of inactivation potential in the layer of water at the bottom of the pool.

Table 8.3. Simulated inactivation potential of *C. parvum* after 1 hour of exposure to sunlight on a mid-summer day at mid-latitude location given the public swimming pool transmittance at 297 nm, 310 nm, and 320 nm wavelength (Particle A1).

	297 nm		**310 nm**		**320 nm**	
Depth (m)	**Dose (mJ/cm²)**	**Log_{10}-Units**	**Dose (mJ/cm²)**	**Log_{10}-Units**	**Dose (mJ/cm²)**	**Log_{10}-Units**
-0.1	2.32E+00	0.08	4.26E+01	0.91	1.29E+02	6.18
-0.3	1.80E+00	0.05	3.46E+01	0.74	1.13E+02	5.23
-0.5	1.38E+00	0.03	2.70E+01	0.58	9.64E+01	4.27
-0.7	1.03E+00	0.02	2.15E+01	0.46	8.08E+01	3.39
-0.9	7.73E-01	0.01	1.71E+01	0.36	7.05E+01	2.81
-1.1	5.84E-01	0.01	1.34E+01	0.29	6.23E+01	2.37
-1.3	4.41E-01	0.00	1.08E+01	0.23	5.61E+01	2.04
-1.5	3.15E-01	0.00	8.25E+00	0.18	5.05E+01	1.75
-1.7	2.46E-01	0.00	6.76E+00	0.14	4.38E+01	1.42
-1.9	1.89E-01	0.00	5.27E+00	0.11	3.68E+01	1.08
-2.1	1.43E-01	0.00	4.47E+00	0.10	3.25E+01	0.89
-2.3	1.03E-01	0.00	3.55E+00	0.08	2.74E+01	0.67
-2.5	8.02E-02	0.00	2.86E+00	0.06	2.43E+01	0.54
-2.7	5.73E-02	0.00	2.29E+00	0.05	2.12E+01	0.43
-2.9	4.01E-02	0.00	1.72E+00	0.04	1.70E+01	0.28

The inactivation potential for the particles in the C3 position at 297 nm, 310 nm and 320 nm are provided in (Table 8.4). After one hour of exposure, these simulations also indicated approximately 6-log_{10} units of inactivation just under the surface due to radiation at 320 nm. This value decreases significantly with increasing depth to only 0.32-log_{10} units of inactivation potential in the layer of water at the bottom of the pool, slightly higher than that at the wall of the pool.

Table 8.4. Simulated inactivation potential of *C. parvum* after 1 hour of exposure to sunlight on a mid-summer day at mid-latitude location given the public swimming pool transmittance at each wavelength (Particle C3).

	297 nm		310 nm		320 nm	
Depth (m)	**Dose (mJ/cm^2)**	**Log_{10}-Units**	**Dose (mJ/cm^2)**	**Log_{10}-Units**	**Dose (mJ/cm^2)**	**Log_{10}-Units**
-0.1	2.35E+00	0.08	3.85E+01	0.82	1.26E+02	6.01
-0.3	1.79E+00	0.05	3.14E+01	0.67	1.11E+02	5.10
-0.5	1.30E+00	0.03	2.49E+01	0.53	9.60E+01	4.25
-0.7	9.74E-01	0.02	2.05E+01	0.44	8.45E+01	3.59
-0.9	7.68E-01	0.01	1.66E+01	0.35	7.43E+01	3.02
-1.1	5.61E-01	0.01	1.28E+01	0.27	6.45E+01	2.49
-1.3	4.47E-01	0.00	1.08E+01	0.23	5.68E+01	2.08
-1.5	3.38E-01	0.00	8.48E+00	0.18	4.74E+01	1.60
-1.7	2.52E-01	0.00	6.88E+00	0.15	4.14E+01	1.30
-1.9	1.89E-01	0.00	5.61E+00	0.12	3.67E+01	1.08
-2.1	1.43E-01	0.00	4.58E+00	0.10	3.24E+01	0.88
-2.3	1.09E-01	0.00	3.55E+00	0.08	2.88E+01	0.72
-2.5	8.02E-02	0.00	2.86E+00	0.06	2.52E+01	0.58
-2.7	6.30E-02	0.00	2.29E+00	0.05	2.19E+01	0.45
-2.9	4.58E-02	0.00	1.83E+00	0.04	1.82E+01	0.32

Table 8.5. provides the inactivation potential for the particles in the A5 position at 297 nm, 310 nm and 320 nm. After one hour of exposure, these simulations also indicated approximately 5-log_{10} units of inactivation just under the surface due to radiation at 320 nm, which is slightly less than that at positions in the pool not shielded by the wall. This value decreases significantly faster than at other points. Below a depth of 0.5 m there was no longer any inactivation potential in the pool from 320 nm radiation.

Table 8.5. Simulated inactivation potential of *C. parvum* after 1 hour of exposure to sunlight on a mid-summer day at mid-latitude location given the public swimming pool transmittance at each wavelength (Particle A5).

	297 nm		310 nm		320 nm	
Depth (m)	**Dose (mJ/cm^2)**	**Log_{10}-Units**	**Dose (mJ/cm^2)**	**Log_{10}-Units**	**Dose (mJ/cm^2)**	**Log_{10}-Units**
-0.1	2.21E+00	0.08	3.71E+01	0.79	1.11E+02	5.15
-0.3	1.19E+00	0.03	2.13E+01	0.45	7.04E+01	2.81
-0.5	4.58E-01	0.00	8.48E+00	0.18	2.84E+01	0.71
-0.7	5.16E-02	0.00	5.73E-01	0.01	2.18E+00	0.00
-0.9	5.73E-03	0.00	0.00E+00	0.00	4.58E-01	0.00
-1.1	5.73E-03	0.00	1.15E-01	0.00	4.58E-01	0.00
-1.3	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
-1.5	5.73E-03	0.00	1.15E-01	0.00	1.15E-01	0.00
-1.7	0.00E+00	0.00	2.29E-01	0.00	1.15E-01	0.00
-1.9	5.73E-03	0.00	1.15E-01	0.00	4.58E-01	0.00
-2.1	5.73E-03	0.00	1.15E-01	0.00	1.15E-01	0.00
-2.3	1.15E-02	0.00	0.00E+00	0.00	0.00E+00	0.00
-2.5	5.73E-03	0.00	2.29E-01	0.00	4.58E-01	0.00
-2.7	0.00E+00	0.00	0.00E+00	0.00	5.73E-01	0.00
-2.9	0.00E+00	0.00	1.15E-01	0.00	1.15E-01	0.00

At all points in the pool, 320 nm was the most influential wavelength in inactivation; 297 nm and 310 nm did not provide over 1-log_{10} unit of inactivation at any point in any set of particles simulated.

These results suggest that solar UVB irradiation could yield substantial inactivation of *C. parvum* oocysts (and other microbial pathogens) in outdoor swimming pools, and that mixing should be explored to induce more even inactivation throughout the pool. However, experiments are needed to verify these predictions and to provide information of the effects of solar UV radiation on *C. parvum* oocysts as a function of water depth, so that the results can be generalized to other outdoor pool settings.

CHAPTER 9. CONCLUSION

The overall goal of this work, was to evaluate the potential for ultraviolet water treatment technologies utilizing ambient solar UV to help address issues of access to safe drinking water in low-income settings. The work spanned an understanding of available ambient solar UV to the implementation of ultraviolet water treatment systems in the Dominican Republic and Kenya. First, the amount of available ambient ultraviolet radiation was quantified to inform the design of reactors that utilize UV directly to inactivate microorganisms. From this information, an existing compound parabolic collector design was optimized through modeling and field testing to increase the water flow rate through the reactor. The flow rate through this improved reactor was not sufficient for providing water at a community scale, and therefore, two commercial UV water disinfection reactors (LP and LED) were tested for disinfection potential in the lab. A household scale LP reactor proved to be the most effective at inactivating *S. typhimurium* LT2, and was used for implementation in water treatment systems moving forward.

This decision was supported by a life cycle assessment of several potential water treatment systems. The LCA showed that chlorine had the smallest environmental impact in all impact categories over all the studied conditions, but non-technical attributes such as the taste of water treated with chlorine, limit its adoption in many communities. The technology with the next lowest impact at a community-scale, which is the scale of field work described herein, was the LP lamp system. LP reactors were installed at four primary schools in the Dominican Republic, and three primary school in Kenya, where one chlorination system was also installed. Implementing water systems in real-world settings allowed identification of barriers to system adoption as well as project shortcomings that are highlighted in this work to improve future studies.

APPENDIX A. SUPPLMENTARY INFORMATION: COMPARATIVE LIFE CYCLE ASSESSMENT OF WATER DISINFECTION PROCESSES FOR APPLICATION IN DEVELOPING COUNTRIES

Table A.1. Characterization factors of TRACI 2.0 methodology.

Impact Category	Characterization Factor
Global Warming	kg CO_2 eq
Acidification	H^+ moles eq
Carcinogenics	benzene eq
Non carcinogenics	toluene eq
Respiratory effects	kg $PM_{2.5}$ eq
Eutrophication	kg N eq
Ozone depletion	kg CFC-11 eq
Ecotoxicity	kg 2,4-D eq
Smog	kg NO_x eq
Fossil Fuel	

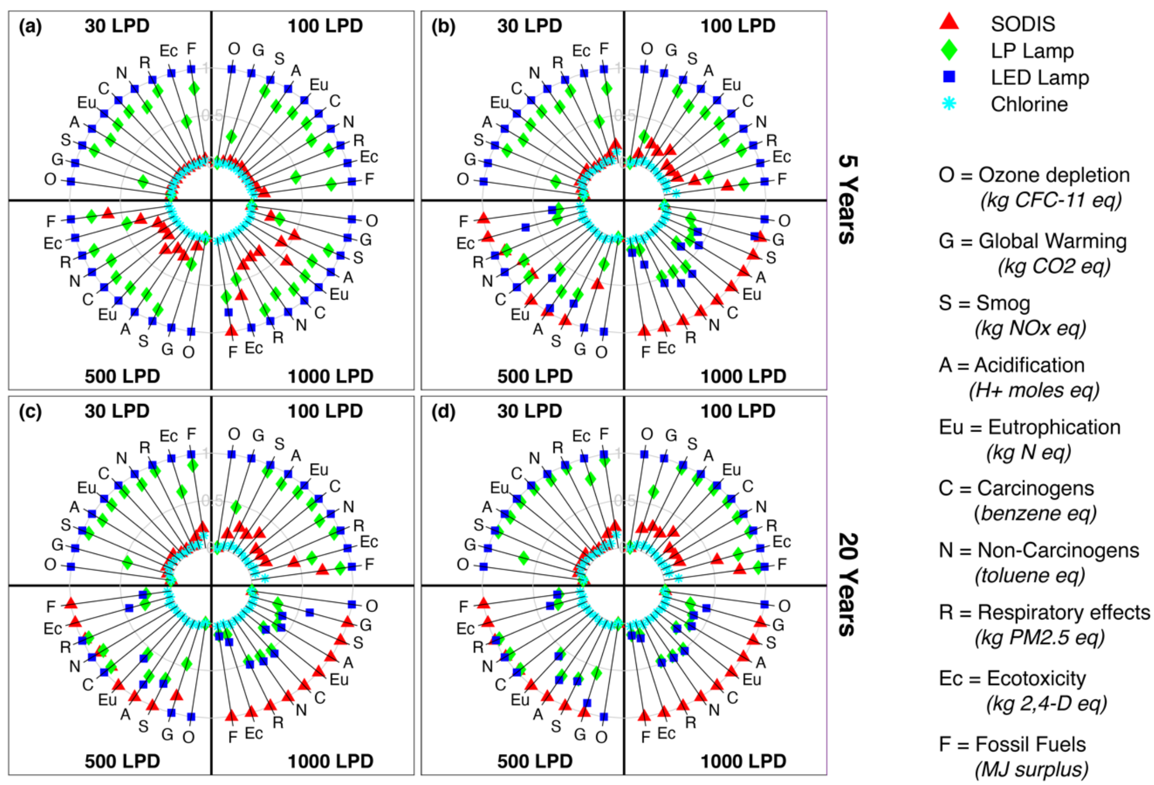

Figure A.1. Comparison of SODIS (▲), the LP reactor (♦), the LED reactor (■), and chlorine (3.8 L) (*) in Kolkata, India. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan in Kolkata, India. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the greatest impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

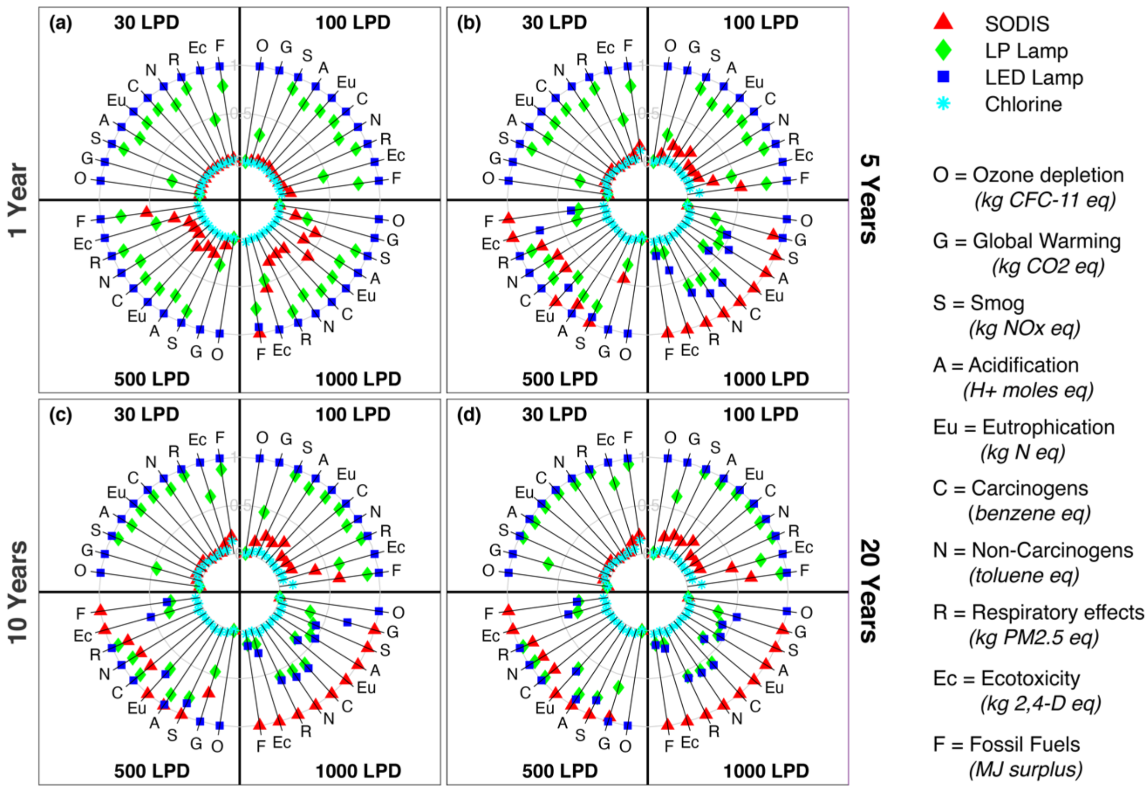

Figure A.2. Comparison of SODIS (▲), the LP reactor (♦), the LED reactor (■), and chlorine (3.8 L) (*) in Nairobi, Kenya. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan in Kolkata, India. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the greatest impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

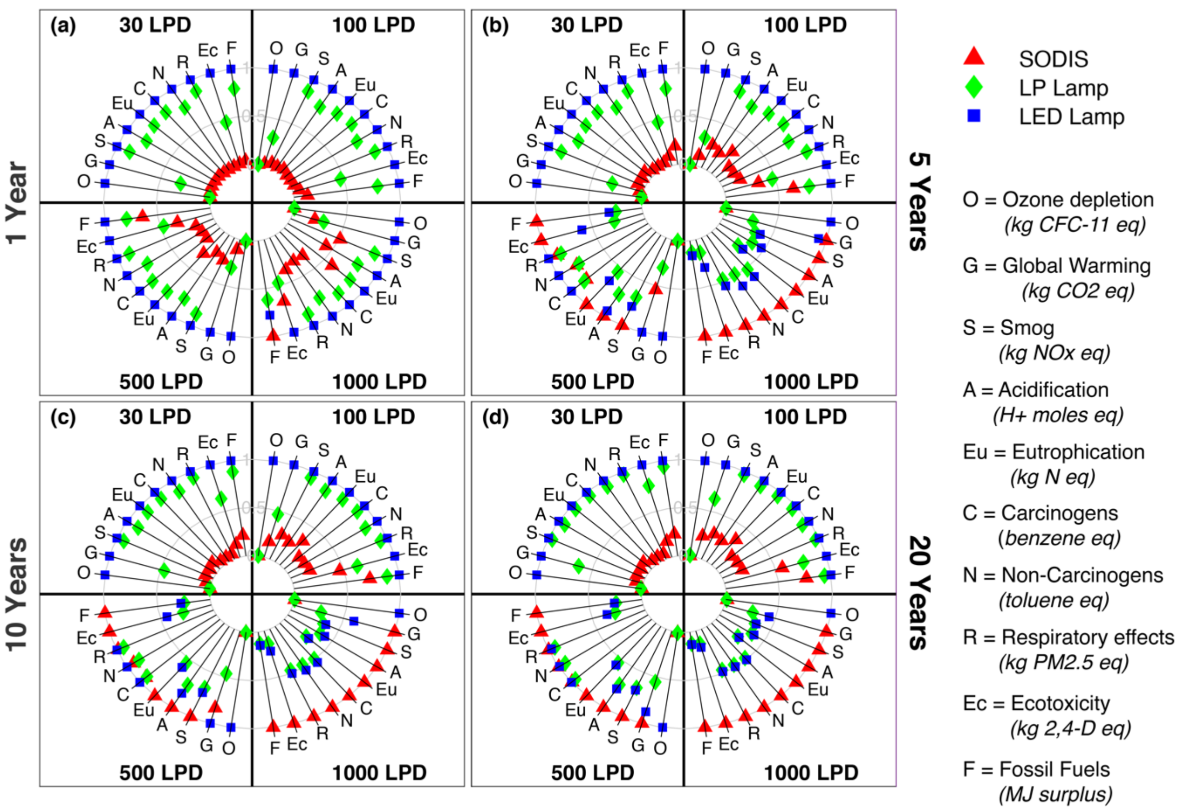

Figure A.3. Comparison of SODIS (▲), the LP reactor (♦), and the LED reactor (■) in Kolkata, India. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan in Kolkata, India. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the greatest impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

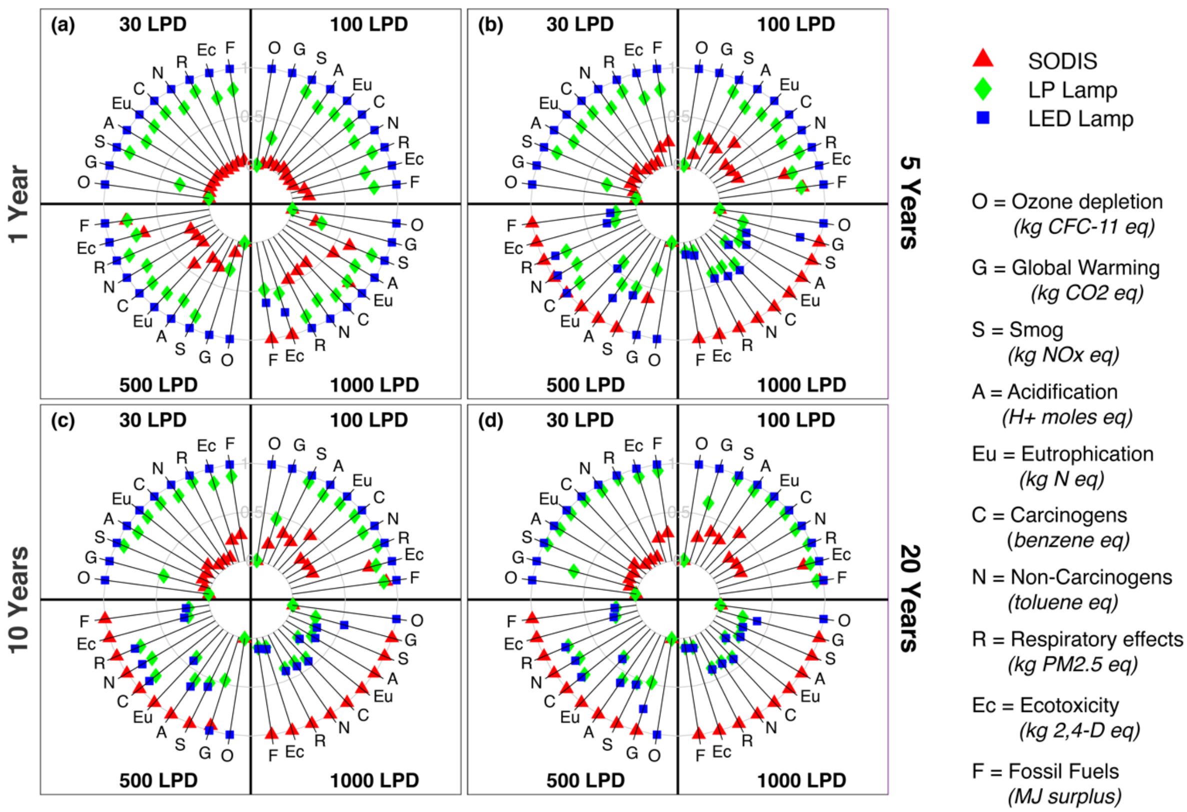

Figure A.4. Comparison of SODIS (PET – 6L) (▲), the LP reactor (♦), and the LED reactor (■) in Nairobi, Kenya with no US end-of-life. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan in Kolkata, India. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the greatest impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

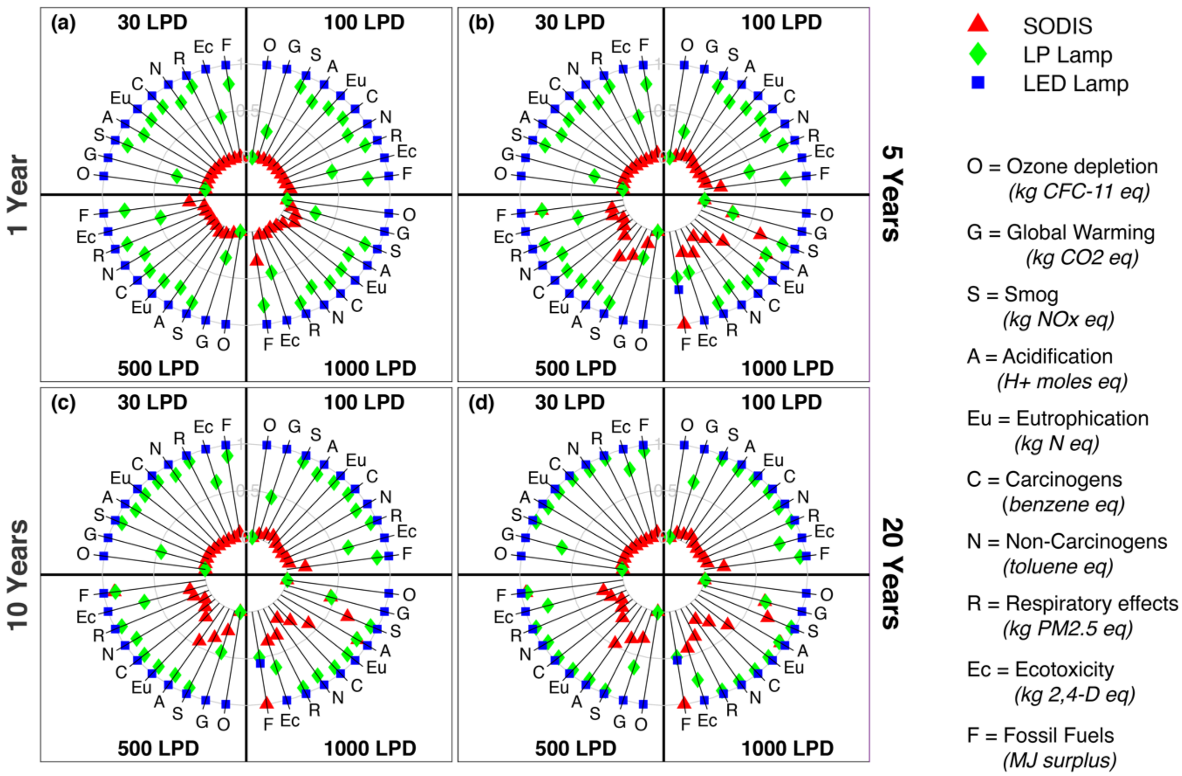

Figure A.5. Comparison of SODIS (PMMA – 6L – 730 day lifespan) (▲), the LP reactor (♦), and the LED reactor (■) in Nairobi, Kenya with no US end-of-life. Each quadrant (a, b, c, and d) represent the studied system lifespan, the sub-quadrants (30 LPD, 100 LPD, 500 LPD, and 1000 LPD) represent different rates of daily water production within each lifespan in Kolkata, India. The radial axes within each sub-quadrant represent the TRACI 2.0 impact categories. The impact in each category under the given set of quadrant and sub-quadrant conditions were normalized by the maximum impact each category of the represented technologies. A normalized impact of 1 represents the greatest impact and is plotted at the outer axis of the radial plot, and smaller impacts are plotted inwards towards the central axis representing 0.

APPENDIX B. SUPPLMENTARY INFORMATION: LESSONS LEARNED THROUGH THE INSTALLATION OF WATER TREATMENT SYSTEMS IN THE DOMINICAN REPUBLIC THROUGH AN INTERDISCIPLINARY, STUDENT-LED, SERVICE-LEARNING COURSE

Table B.1. Percentage of respondents that believe their water is safe to drink based on the source of water in each community.

		Dry							Rainy						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
School 2	Piped water into dwelling	0.0%	0.0%	0.0%	25.0%	25.0%	25.0%	25.0%	-	-	-	-	-	-	-
	Piped water into yard, plot	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-	-	-	-	-	-	-
	Public well, standpipe	0.0%	0.0%	2.6%	21.1%	31.6%	36.8%	7.9%	0.0%	0.0%	0.0%	18.2%	33.3%	39.4%	9.1%
	Household rainwater collection	1.1%	1.1%	6.7%	25.6%	12.2%	14.4%	38.9%	1.1%	0.6%	5.7%	23.3%	18.8%	21.6%	29.0%
	Truck that fills cistern	0.0%	0.0%	0.0%	9.4%	43.8%	43.8%	3.1%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
	Bottles delivered by truck	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Bottles bought from store	2.3%	0.0%	3.8%	15.9%	12.9%	29.5%	35.6%	2.2%	0.0%	4.4%	11.0%	8.8%	36.3%	37.4%
	Surface water (river, pond, lake)	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%
	Other	-	-	-	-	-	-	-	-	-	-	-	-	-	-
School 3	Piped water into dwelling	0.0%	7.7%	15.4%	23.1%	15.4%	30.8%	7.7%	0.0%	0.0%	11.5%	23.1%	19.2%	23.1%	23.1%
	Piped water into yard, plot	0.0%	0.0%	16.7%	16.7%	0.0%	50.0%	16.7%	0.0%	0.0%	30.0%	30.0%	0.0%	10.0%	30.0%
	Public well, standpipe	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%
	Household rainwater collection	0.0%	5.6%	16.7%	11.1%	27.8%	33.3%	5.6%	0.0%	2.5%	5.0%	5.0%	42.5%	32.5%	12.5%
	Truck that fills cistern	0.0%	0.0%	3.7%	11.1%	29.6%	33.3%	22.2%	0.0%	0.0%	8.3%	0.0%	41.7%	33.3%	16.7%
	Bottles delivered by truck	0.0%	33.3%	0.0%	0.0%	0.0%	66.7%	0.0%	50.0%	0.0%	0.0%	0.0%	12.5%	37.5%	0.0%
	Bottles bought from store	12.4%	3.5%	2.9%	7.1%	28.2%	30.6%	15.3%	12.7%	4.8%	2.4%	8.5%	27.9%	29.7%	13.9%
	Surface water (river, pond, lake)	-	-	-	-	-	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	Other	-	-	-	-	-	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%
School 4	Piped water into dwelling	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Piped water into yard, plot	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Public well, standpipe	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Household rainwater collection	13.3%	20.0%	6.7%	26.7%	20.0%	6.7%	6.7%	8.3%	27.8%	19.4%	19.4%	16.7%	2.8%	5.6%
	Truck that fills cistern	50.0%	0.0%	0.0%	25.0%	0.0%	0.0%	25.0%	66.7%	33.3%	0.0%	0.0%	0.0%	0.0%	0.0%
	Bottles delivered by truck	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Bottles bought from store	23.4%	41.6%	13.0%	10.4%	5.2%	1.3%	5.2%	23.9%	44.8%	11.9%	9.0%	4.5%	1.5%	4.5%
	Surface water (river, pond, lake)	50.0%	0.0%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%
	Other	-	-	-	-	-	-	-	-	-	-	-	-	-	-

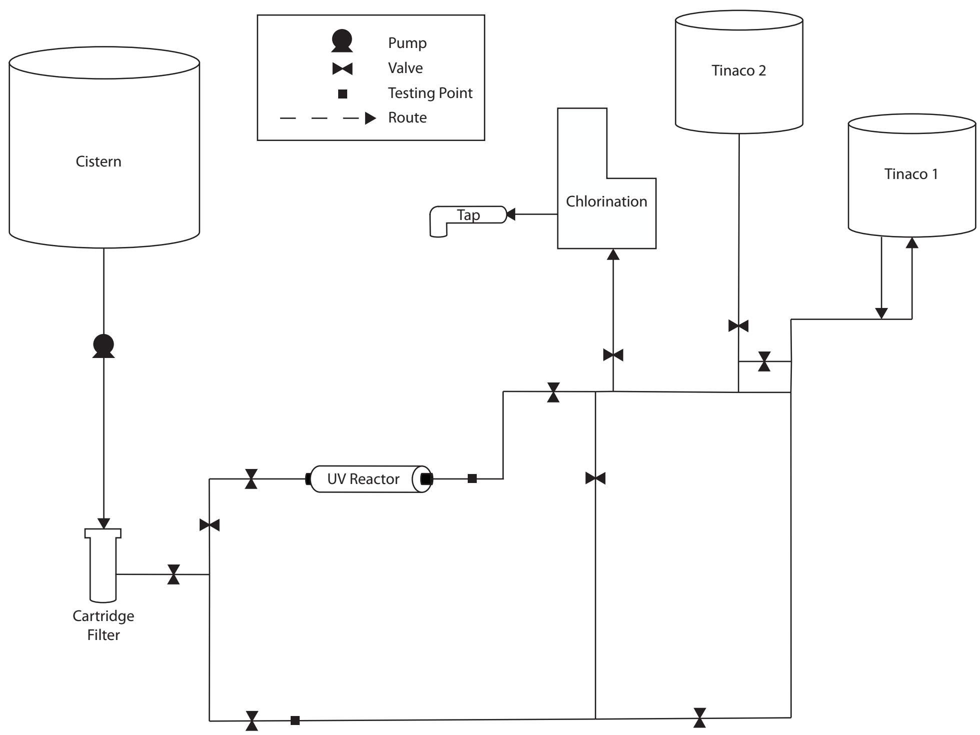

Figure B.1. Flow of water through the second water treatment system.

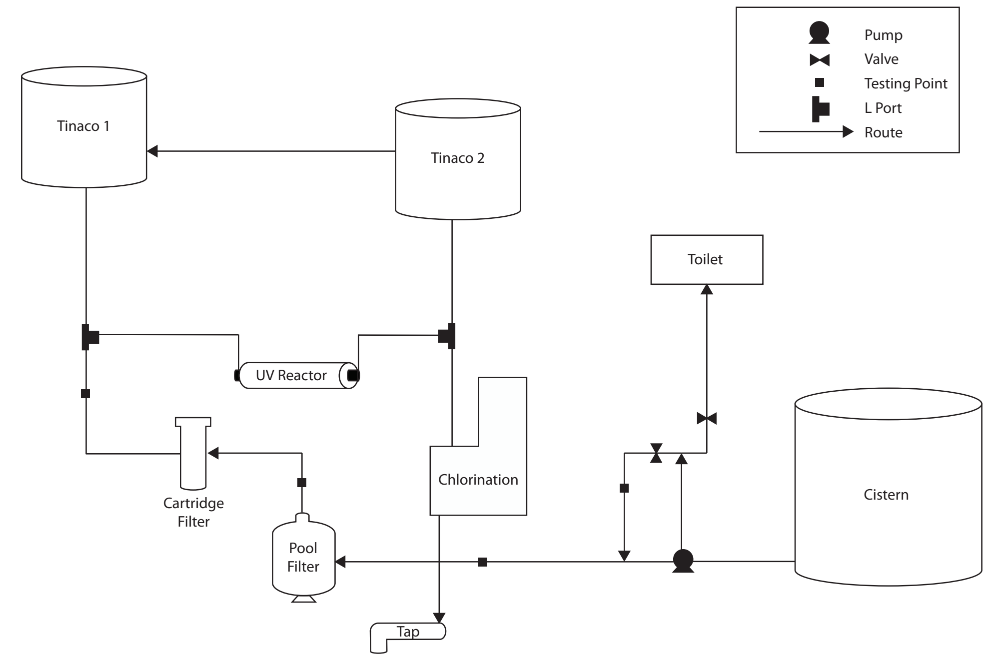

Figure B.2. Flow of water through the third water treatment system.

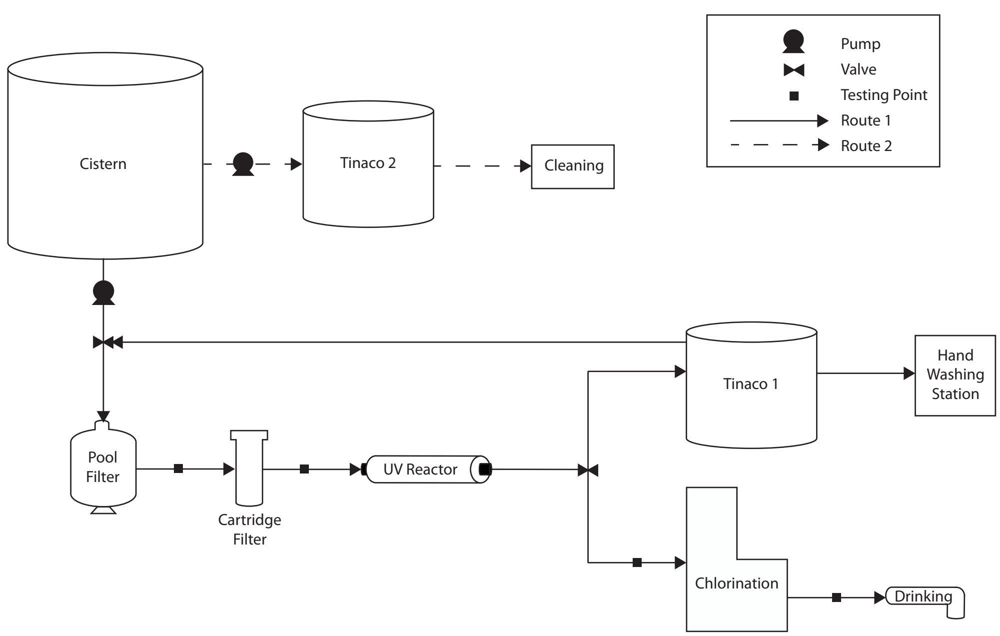

Figure B.3. Flow of water through the fourth water treatment system.

APPENDIX C. SUPPLMENTARY INFORMATION: LESSONS FROM THE IMPLEMENTATION OF SCHOOL-MANAGED DRINKING WATER TREATMENT TECHNOLOGIES IN USAIN GISHU COUNTY, KENYA

For system testing, guideline values of basic water quality parameters important to the operation of the UV system included UV_{254}transmittance greater than 75%, <0.3 mg/L iron, <7 gpg hardness, <1 NTU turbidity, <0.05 mg/L manganese and < 0.1 mg/L tannins. Transmittance was measured with the UVT 100 Meter from UV Dynamics UV Systems as a low cost, high fidelity option. Turbidity (NTU) was measured with a Hach portable turbidimeter (2100P), and Hach 5-in-1 water quality test strips were used to measure total hardness (as $CaCO_3$, 0-25 gpg and 0-425 mg/L). They also provided data on free chlorine (0-10mg/L), total chlorine (0-10 mg/L), total alkalinity (as $CaCO_3$, 0-240 mg/L) and pH (6.2 - 8.4) of water samples. An Apera Instruments Pocket Tester was used to measure pH, conductivity (EC), salinity (ppt), resistivity and temperature. There were no available portable instruments for collecting water quality data on iron, manganese or tannins.

For the chlorine system, important water quality parameters included turbidity, pH, total chlorine, and free chlorine. Turbidity was again measured using the Hach turbidimeter, and Hach 5-in-1 water quality test strips were used to measure free chlorine (0-10 mg/L), total chlorine (0-10 mg/L), and pH (6.2 - 8.4). HF Scientific™ Chlorine Micro Check Test Strips were also used to measure free chlorine (range of detection: 0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.2, 1.5, 2.0, 2.6, 4.0, 6.0, 10 mg/L).

Compartment bag tests (CBTs) were purchased from Aquagenx to measure the most probable number (MPN) of viable *E. coli* in influent and effluent water samples. Viable *E. coli* concentration data were used as an indication of water quality in terms of microbial composition.

Water quality testing was to be conducted by an employee of our local partner, Maji Safi, using an Android tablet (Lenovo Tab 10, Android 6.0 operating system) to upload test results in a form designed in KoboToolbox (https://www.kobotoolbox.org/) once per week. KoboToolbox was selected because of its offline data collection ability. Surveys/forms can be accessed and submitted offline, and once the tablet is connected to Wi-Fi, the results will automatically upload to the KoboToolbox data based. Data can then be accessed from anywhere.

The intended method for data collection of the water treatment systems was unsuccessful due to proximity of schools to the Maji Safi employee's place of work in Eldoret (1 hr drive to each location – would take 4 hours per week just in travel), and an inability to find funds for compensating his time. Therefore, on a follow-up visit, we spoke with the schools and arranged for the maintenance employee who works at schools A, B, and C to operate, maintain, and test the systems, but starting with one less data collection tool (only the Apera test meter and CBTs). We wanted to establish a data collection habit before introducing more instruments. He was trained to upload the results to KoboToolbox on the provided tablet. The director of school D agreed to operate, maintain, and test for chlorine using test strips and record the results on paper.

On the second follow-up trip, it was learned that the employee from School A was uncomfortable with the data collection process, which is why data were not received. He still had the testing equipment, but the Apera probe has not been kept in the proper solution, therefore, it was no longer operating correctly. We had acquired an updated Apera testing meter, so the maintenance employee, the head teacher, and the head science teacher were trained on the new test meter, which is now kept at the school. They were provided a paper form to record these data for each of the schools (A, B, and C) each day and periodically transmitted the results to our team via WhatsApp. This happened for only school A, for the first month after the trip, but then schools were closed due to COVID-19. We have not received any test results from school D.

REFERENCES

Acra, A., Raffoul, Z., Karahagopian, Y., 1984. Solar disinfection of drinking water and oral rehydration solutions. Illustrated Publications S.A.L.,Beirut, Lebanon, Lebanon.

Albert, J., Luoto, J., Levine, D., 2010. End-user preferences for and performance of competing POU water treatment technologies among the rural poor of Kenya. Environmental Science & Technology 44, 4426–4432. https://doi.org/10.1021/es1000566

Alexandrov, M.D., Kiedron, P., Michalsky, J.J., Hodges, G., Flynn, C.J., Lacis, A. a, 2007. Optical Depth Measurements by Shadow-band Radiometers and their Uncertainties. Applied Optics 46, 8027–8038.

Ali, S.I., 2010. Alternatives for safe water provision in urban and peri-urban slums. JOURNAL OF WATER AND HEALTH 8, 720–734. https://doi.org/10.2166/wh.2010.141

Alwang, A., Busse, M., Caprio, A., Fenton, M., Hawes, J., Kanach, A., McElfresh-Sutton, A., 2017. Water Supply in Developing Countries: Student Experiences in the Dominican Republic. Purdue Journal of Service-Learning and International Engagement 4, 27–34. https://doi.org/10.5703/1288284316525

Amin, N., Crider, Y.S., Unicomb, L., Das, K.K., Gope, P.S., Mahmud, Z.H., Islam, M.S., Davis, J., Luby, S.P., Pickering, A.J., 2016. Field trial of an automated batch chlorinator system at shared water points in an urban community of Dhaka, Bangladesh. Journal of Water, Sanitation and Hygiene for Development 6, 32–41. https://doi.org/10.2166/washdev.2016.027

Arnold, B.F., Colford, J.M., 2007. Treating Water with Chlorine at Point-of-Use to Improve Water Quality and Reduce Child Diarrhea in Developing Countries: A Systematic Review and Meta-Analysis. The American Journal of Tropical Medicine and Hygiene 76, 354–364. https://doi.org/10.4269/ajtmh.2007.76.354

Barstow, C.K., Dotson, A.D., Linden, K.G., 2014. Assessing point-of-use ultraviolet disinfection for safe water in urban developing communities. Journal of Water and Health 12, 663–669. https://doi.org/10.2166/wh.2014.223

Baum, R., Kayser, G., Stauber, C., Sobsey, M., 2014. Assessing the microbial quality of improved drinking water sources: Results from the Dominican Republic. American Journal of Tropical Medicine and Hygiene 90, 121–123. https://doi.org/10.4269/ajtmh.13-0380

Blake, E., Tucker, W., Glaser, M., 2014. Towards communication and information access for Deaf people 10.

Bresee, S., Caruso, B.A., Sales, J., Lupele, J., Freeman, M.C., 2016. "A child is also a teacher": Exploring the potential for children as change agents in the context of a school-based WASH intervention in rural Eastern Zambia. Health Education Research 31, 521–534. https://doi.org/10.1093/her/cyw022

Buntoung, S., Webb, a. R., 2010. Comparison of erythemal UV irradiances from Ozone Monitoring Instrument (OMI) and ground-based data at four Thai stations. Journal of Geophysical Research: Atmospheres 115, 1–8.

Busse, M.M., 2016. Characterization of a Continuous-Flow Reactor for Solar UV Water Disinfection. https://doi.org/10.1017/CBO9781107415324.004

Busse, M.M., Becker, M., Applegate, B.M., Camp, J.W., Blatchley, E.R., 2019. Responses of Salmonella typhimurium LT2, Vibrio harveyi, and Cryptosporidium parvum to UVB and UVA Radiation. Chemical Engineering Journal 371, 647–656. https://doi.org/10.1016/j.cej.2019.04.105

Caruso, B.A., Freeman, M.C., Garn, J.V., Dreibelbis, R., Saboori, S., Muga, R., Rheingans, R., 2014. Assessing the impact of a school-based latrine cleaning and handwashing program on pupil absence in Nyanza Province, Kenya: a cluster-randomized trial. Trop Med Int Health 19, 1185–1197. https://doi.org/10.1111/tmi.12360

Cashman, S., Gaglione, A., Mosley, J., Weiss, L., Hawkins, T.R., Ashbolt, N.J., Cashdollar, J., Xue, X., Ma, C., Arden, S., 2014. Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Drinking Water Treatment 104.

Cherunya, P.C., Janezic, C., Leuchner, M., 2015. Sustainable supply of safe drinking water for underserved households in Kenya: Investigating the viability of decentralized solutions. Water (Switzerland) 7, 5437–5457. https://doi.org/10.3390/w7105437

Christensen, G., Dentz, H.N., Pickering, A.J., Bourdier, T., Arnold, B.F., Colford, J.M., Null, C., 2015. Pilot Cluster Randomized Controlled Trials to Evaluate Adoption of Water, Sanitation, and Hygiene Interventions and Their Combination in Rural Western Kenya. The American Journal of Tropical Medicine and Hygiene 92, 437–447. https://doi.org/10.4269/ajtmh.14-0138

Clasen, T., Haller, L., Walker, D., Bartram, J., Cairncross, S., 2007. Cost-effectiveness of water quality interventions for preventing diarrhoeal disease in developing countries. Journal of Water and Health 5, 599–608. https://doi.org/10.2166/wh.2007.010

Clasen, T.F., Alexander, K.T., Sinclair, D., Boisson, S., Peletz, R., Chang, H.H., Majorin, F., Cairncross, S., 2015. Interventions to improve water quality for preventing diarrhoea. Cochrane Database of Systematic Reviews CD004794. https://doi.org/10.1002/14651858.CD004794.pub3.www.cochranelibrary.com

Coelho, S.T., James, S., Sunna, N., Abu Jaish, A., Chatiia, J., 2003. Controlling water quality in intermittent supply systems. Water Science and Technology: Water Supply 3, 119–125. https://doi.org/10.2166/ws.2003.0094

Connolly, M., 1990. Adrift in the City:: A Comparative Study of Street Children in Bogotá, Colombia, and Guatemala City. Child & Youth Services 14, 129–149. https://doi.org/10.1300/J024v14n01_09

Crabtree, R.D., 2013. The Intended and Unintended Consequences of International Service-Learning. Journal of Higher Education Outreach and Engagement 17, 7–41. https://doi.org/10.5840/acpq201622982

Crider, Y., Sultana, S., Unicomb, L., Davis, J., Luby, S.P., Pickering, A.J., 2018a. Can you taste it? Taste detection and acceptability thresholds for chlorine residual in drinking water in Dhaka, Bangladesh. Science of the Total Environment 613–614, 840–846. https://doi.org/10.1016/j.scitotenv.2017.09.135

Crider, Y., Sultana, S., Unicomb, L., Davis, J., Luby, S.P., Pickering, A.J., 2018b. Can you taste it? Taste detection and acceptability thresholds for chlorine residual in drinking water in Dhaka, Bangladesh. Science of The Total Environment 613–614, 840–846. https://doi.org/10.1016/j.scitotenv.2017.09.135

Dacunto, P., Varriano, V.R., Ko, J., 2015. Project-based Learning in the Developing World: Design of a Modular Water Collection and Treatment System, in: Seattle Making Value for Society. Presented at the 122nd ASEE Annual Conference and Exposition, Seattle, WA, USA, p. 14.

Das, T.K., 2002. Evaluating the life cycle environmental performance of chlorine disinfection and ultraviolet technologies. Clean Technologies and Environmental Policy 4, 32–43. https://doi.org/10.1007/s10098-002-0139-x

Diergaardt, G.F., Lemmer, T.N., 1995. Alternative disinfection methods for small water supply schemes with chlorination problems. Water supply: the review journal of the International Water Supply Association.

Dreibelbis, R., Winch, P.J., Leontsini, E., Hulland, K.R., Ram, P.K., Unicomb, L., Luby, S.P., 2013. The Integrated Behavioural Model for Water, Sanitation, and Hygiene: a systematic review of behavioural models and a framework for designing and evaluating behaviour change interventions in infrastructure-restricted settings. BMC Public Health 13, 1015. https://doi.org/10.1186/1471-2458-13-1015

EPA, 2019. Advancing Sustainable Materials Management: Facts and Figures Report. United States Environmental Protection Agency.

Fewtrell, L., Colford, J.M., 2005. Water, sanitation and hygiene in developing countries: Interventions and diarrhoea-a review. Water Science and Technology 52, 133–142. https://doi.org/10.2166/wst.2005.0244

Fisher, M.B., Iriarte, M., Nelson, K.L., 2012. Solar water disinfection (SODIS) of Escherichia coli, Enterococcus spp., and MS2 coliphage: Effects of additives and alternative container materials. Water Research 46, 1745–1754. https://doi.org/10.1016/j.watres.2011.12.048

Fisher, M.B., Keenan, C.R., Nelson, K.L., Voelker, B.M., 2008. Speeding up Solar Disinfection (SODIS): Effects of Hydrogen Peroxide, Temperature, pH, and Copper plus Ascorbate on the Photoinactivation of E. coli. Journal of Water and Health 6, 35.

Frederick, J.E., Snell, H.E., Haywood, E.K., 1989. Solar Ultraviolet Radiation At the Earth's Surface. Photochemistry and Photobiology 50, 443–450. https://doi.org/10.1111/j.1751-1097.1989.tb05548.x

Freeman, M.C., Quick, R.E., Abbott, D.P., Ogutu, P., Rheingans, R., 2009. Increasing equity of access to point-of-use water treatment products through social marketing and entrepreneurship: A case study in western Kenya. Journal of Water and Health 7, 527–534. https://doi.org/10.2166/wh.2009.063

García-Ávila, F., Avilés-Añazco, A., Sánchez-Cordero, E., Valdiviezo-Gonzáles, L., Ordoñez, M.D.T., 2021. The challenge of improving the efficiency of drinking water treatment systems in rural areas facing changes in the raw water quality. South African Journal of Chemical Engineering 37, 141–149. https://doi.org/10.1016/j.sajce.2021.05.010

García-Gil, Á., Pablos, C., García-Muñoz, R.A., McGuigan, K.G., Marugán, J., 2020. Material selection and prediction of solar irradiance in plastic devices for application of solar water disinfection (SODIS) to inactivate viruses, bacteria and protozoa. Science of the Total Environment 730, 139126. https://doi.org/10.1016/j.scitotenv.2020.139126

Garfí, M., Cadena, E., Sanchez-Ramos, D., Ferrer, I., 2016. Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. Journal of Cleaner Production 137, 997–1003. https://doi.org/10.1016/j.jclepro.2016.07.218

Gez, Y.N., 2021. The Afterlives of International Development Interventions: A Site-Specific Ethnographic Approach. Journal of Development Studies 57, 1511–1526. https://doi.org/10.1080/00220388.2021.1873288

Gill, L. W., Price, C., 2010. Preliminary observations of a continuous flow solar disinfection system for a rural community in Kenya. Energy 35, 4607–4611. https://doi.org/10.1016/j.energy.2010.01.008

Gill, L.W., Price, C., 2010. Preliminary observations of a continuous flow solar disinfection system for a rural community in Kenya. Energy 35, 4607–4611. https://doi.org/10.1016/j.energy.2010.01.008

Gold, M., Thomas, E., Byyny, R., Habanabakize, J.P., 2012. Development and Implementation of the Bring Your Own Water Treatment System in Dense, Rural, and Mountainous Rwandan Communities . Journal of Engineering for Sustainable Community Development 1, 10–28. https://doi.org/10.3992/2166-2517-1.2.10

Gómez-Couso, H., Fontán-Sainz, M., Fernández-Ibáñez, P., Ares-Mazás, E., 2012. Speeding up the Solar Water Disinfection Process (SODIS) Against Cryptosporidium parvum by Using 2.5l Static Solar Reactors Fitted with Compound Parabolic Concentrators (CPCs). Acta Tropica 124, 235–242.

Grady, C.A., Kipkorir, E.C., Nguyen, K., Blatchley III, E.R., 2015. Microbial Quality of Improved Drinking Water Sources: Evidence from Western Kenya and Southern Vietnam. Journal of Water & Health 13, 607–612.

Grant, R.H., Heisler, G.M., 2000. Estimation of Ultraviolet-B Irradiance under Variable Cloud Conditions. Journal of Applied Meteorology 39, 904–916. https://doi.org/10.1175/1520-0450(2000)039<0904:EOUBIU>2.0.CO;2

Guchi, E., 2015a. Review on Slow Sand Filtration in Removing Microbial Contamination and Particles from Drinking Water. American Journal of Food and Nutrition 3, 47–55. https://doi.org/10.12691/ajfn-3-2-3

Guchi, E., 2015b. Review on Slow Sand Filtration in Removing Microbial Contamination and Particles from Drinking Water. American Journal of Food and Nutrition 10.

Gutiérrez-Alfaro, S., Acevedo, A., Figueredo, M., Saladin, M., Manzano, M.A., 2017. Accelerating the process of solar disinfection (SODIS) by using polymer bags: Accelerating solar disinfection (SODIS) by using polymer bags. J. Chem. Technol. Biotechnol. 92, 298–304. https://doi.org/10.1002/jctb.5005

Harding, A.S., Schwab, K.J., 2012. Using limes and synthetic psoralens to enhance solar disinfection of water (SODIS): A laboratory evaluation with norovirus, Escherichia coli, and MS2. American Journal of Tropical Medicine and Hygiene 86, 566–572. https://doi.org/10.4269/ajtmh.2012.11-0370

Hlavsa, M.C., Roberts, V., Anderson, A.R., Hill, V.R., Kahler, A.M., Orr, M., Garrison, L.E., Hicks, L.A., Newton, A., Hilborn, E.D., Wade, T.J., Beach, M.J., Yoder, J.S., 2011. Surveillance for waterborne disease and outbreaks associated with recreational water use and other aquatic facility-associated health events - United States, 2007-2008, Morbidity and Mortality Weekly Report.

Howard, J.P.F., 1998. Academic service learning: A counternormative pedagogy. New Directions for Teaching and Learning 1998, 21–29. https://doi.org/10.1002/tl.7303

Hrudey, S.E., Hrudey, E.J., 2004. Safe Drinking Water: Lessons from Recent Outbreaks in Affluent Nations. IWA Publishing.

International Standard Organization, 2016. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework.

IUPAC, 1997. Compendium of Chemical Terminology, in: McNaught, A.D., Wilkinson, A. (Eds.), The "Gold Book." Blackwell Scientific Publications, Oxford. https://doi.org/10.1351/goldbook.FT07376

Jadhav, A.S., Gudekar, A.S., Patil, R.G., Kale, D.M., Panse, S. V., Joshi, J.B., 2013. Performance analysis of a novel and cost effective CPC system. Energy Conversion and Management 66, 56–65. https://doi.org/10.1016/j.enconman.2012.09.030

Jones, C.H., Shilling, E.G., Linden, K.G., Cook, S.M., 2018. Life Cycle Environmental Impacts of Disinfection Technologies Used in Small Drinking Water Systems. Environmental Science and Technology 52, 2998–3007. https://doi.org/10.1021/acs.est.7b04448

Kehoe, S.C., Joyce, T.M., Ibrahim, P., Gillespie, J.B., Shahar, R.A., McGuigan, K.G., 2001. Effect of Agitation, Turbidity, Aluminium Foil reflectors and Container Volume on the Inactivation Efficiency of Batch-process Solar Disinfectors. Water Research 35, 1061–1065.

Kibet, V.K., 2013. The Effect of Household Background Characteristics and Asset Portfolios (Capital) on Student's Academic Achievement in Kenya Certificate of Primary Education (K.C.P.E.): A Case of Baringo County. University of Nairobi.

KNBS, 2014. Kenya Demographic and Health Survey 2014. Nairobi, Kenya.

Kothari, U., 2005. From colonial administration to development studies: A post-colonial critique of the history of development studies. Zed Books, pp. 47–66.

Kotlarz, N., Lantagne, D., Preston, K., Jellison, K., 2009. Turbidity and chlorine demand reduction using locally available physical water clarification mechanisms before household chlorination in developing countries. JOURNAL OF WATER AND HEALTH 7, 497–506. https://doi.org/10.2166/wh.2009.071

Lach, D., 2014a. Challenges of interdisciplinary research: Reconciling qualitative and quantitative methods for understanding human-landscape systems. Environmental Management 53, 88–93. https://doi.org/10.1007/s00267-013-0115-8

Lach, D., 2014b. Challenges of Interdisciplinary Research: Reconciling Qualitative and Quantitative Methods for Understanding Human–Landscape Systems. Environmental Management 53, 88–93. https://doi.org/10.1007/s00267-013-0115-8

Lantagne, D.S., Quick, R., Mintz, E.D., 2006. Household water treatment and safe storage options in developing countries: a review of current implementation practices. Environmental Change and Security Program 17–38. https://doi.org/10.1021/es301842u

Lawrie, K., Mills, A., Figueredo-Fernández, M., Gutiérrez-Alfaro, S., Manzano, M., Saladin, M., 2015. UV dosimetry for solar water disinfection (SODIS) carried out in different plastic bottles and bags. Sensors and Actuators B: Chemical 208, 608–615. https://doi.org/10.1016/j.snb.2014.11.031

Lee, E.J., Schwab, K.J., 2005. Deficiencies in Drinking Water Distribution Systems in Developing Countries. Journal of water and health 3, 109–127.

Lemos, D., Dias, A.C., Gabarrell, X., Arroja, L., 2013. Environmental assessment of an urban water system. Journal of Cleaner Production 54, 157–165. https://doi.org/10.1016/j.jclepro.2013.04.029

LTI Optics, 2014. Photopia User's Guide.

Luby, S.P., Mendoza, C., Keswick, B.H., Chiller, T.M., Hoekstra, R.M., 2008. Difficulties in Bringing Point-of-Use Water Treatment to Scale in Rural Guatemala. The American Society of Tropical Medicine and Hygiene 78, 382–387.

Lucas, A.M., Mbiti, I.M., 2012. Access, Sorting, and Achievement: The Short-Run Effects of Free Primary Education in Kenya. American Economic Journal: Applied Economics 4, 226–253.

Luoto, J., Najnin, N., Mahmud, M., Albert, J., Islam, M.S., Luby, S., Unicomb, L., Levine, D.I., 2011. What point-of-use water treatment products do consumers use? Evidence from a randomized controlled trial among the urban poor in Bangladesh. PLoS ONE 6. https://doi.org/10.1371/journal.pone.0026132

Luzi, S., Tobler, M., Suter, F., Meierhofer, R., 2016. SODIS Manual [WWW Document]. Swiss Federal Institute of Aquatic Science and Technology.

Mac Mahon, J., Gill, L.W., 2018. Sustainability of novel water treatment technologies in developing countries: Lessons learned from research trials on a pilot continuous flow solar water disinfection system in rural Kenya. Development Engineering 3, 47–59. https://doi.org/10.1016/j.deveng.2018.01.003

Madronich, S., Wagner, M., Groth, P., 2011. Influence of Tropospheric Ozone Control on Exposure to Ultraviolet Radiation at the Surface. Environmental Science & Technology 45, 6919–23.

Malato, S., Fernández-Ibáñez, P., Maldonado, M.I., Blanco, J., Gernjak, W., 2009. Decontamination and Disinfection of Water by Solar Photocatalysis: Recent Overview and Trends. Catalysis Today 147, 1–59.

Mallevialle, J., Suffet, I.H., 1987. Identification and treatment of tastes and odors in drinking water. American Water Works Association.

Mani, S.K., Kanjur, R., Bright Singh, I.S., Reed, R.H., 2006. Comparative effectiveness of solar disinfection using small-scale batch reactors with reflective, absorptive and transmissive rear surfaces. Water Research 40, 721–727. https://doi.org/10.1016/j.watres.2005.11.039

Markus, G.B., Howard, J.P.F., King, D.C., 1993. Notes: Integrating Community Service and Classroom Instruction Enhances Learning: Results From an Experiment. Educational Evaluation and Policy Analysis 15, 410–419. https://doi.org/10.3102/01623737015004410

Mbonimpa, E.G., Vadheim, B., Blatchley III, E.R., 2012. Continuous-flow Solar UVB Disinfection Reactor for Drinking Water. Water Research 46, 2344–54. https://doi.org/10.1016/j.watres.2012.02.003

McGuigan, K.G., Conroy, R.M., Mosler, H.J., du Preez, M., Ubomba-Jaswa, E., Fernandez-Ibañez, P., 2012. Solar water disinfection (SODIS): A review from bench-top to roof-top. Journal of Hazardous Materials 235–236, 29–46. https://doi.org/10.1016/j.jhazmat.2012.07.053

McGuigan, K.G., Joyce, T.M., Conroy, R.M., Gillespie, J.B., Elmore-Meegan, M., 1998. Solar disinfection of drinking water contained in transparent plastic bottles: Characterizing the bacterial inactivation process. Journal of Applied Microbiology 84, 1138–1148. https://doi.org/10.1046/j.1365-2672.1998.00455.x

Morinville, C., 2017. Sachet water: regulation and implications for access and equity in Accra, Ghana. WIREs Water 4. https://doi.org/10.1002/wat2.1244

Mundada, M.N., Kumar, S., Shekdar, A. V., 2004. E-waste: A new challenge for waste management in India. International Journal of Environmental Studies 61, 265–279. https://doi.org/10.1080/0020723042000176060

Mwanga, J.R., Jensen, B.B., Magnussen, P., Aagaard-Hansen, J., 2008. School children as health change agents in Magu, Tanzania: A feasibility study. Health Promotion International 23, 16–23. https://doi.org/10.1093/heapro/dam037

Nalwanga, R., Quilty, B., Muyanja, C., Fernandez-Ibañez, P., McGuigan, K.G., 2014. Evaluation of solar disinfection of E. coli under Sub-Saharan field conditions using a 25L borosilicate glass batch reactor fitted with a compound parabolic collector. Solar Energy 100, 195–202. https://doi.org/10.1016/j.solener.2013.12.011

Nauges, C., Whittington, D., 2010. Estimation of Water Demand in Developing Countries: An Overview. World Bank Research Observer 25, 263–294. https://doi.org/10.1093/wbro/lkp016

Olayiwole, C.B., Ezirim, Okoro, G.C., 2003. Children as agents of sanitation and hygiene behaviour change, in: 29th WEDC International Conference. pp. 55–57.

Onyango-Ouma, W., Aagaard-Hansen, J., Jensen, B.B., 2005. The potential of schoolchildren as health change agents in rural western Kenya. Social Science & Medicine 61, 1711–1722. https://doi.org/10.1016/j.socscimed.2005.03.041

Onyango-Ouma, W., Gerba, C.P., 2011. Away-from-home drinking water consumption practices and the microbiological quality of water consumed in rural western Kenya. Journal of Water and Health 9, 628–636. https://doi.org/10.2166/wh.2011.115

Palancar, G.G., Toselli, B.M., 2004. Effects of Meteorology and Tropospheric Aerosols on UV-B Radiation: A 4-year Study. Atmospheric Environment 38, 2749–2757.

Parker Fiebelkorn, A., Person, B., Quick, R.E., Vindigni, S.M., Jhung, M., Bowen, A., Riley, P.L., 2012a. Systematic review of behavior change research on point-of-use water treatment interventions in countries categorized as low- to medium-development on the human development index. Social Science and Medicine 75, 622–633. https://doi.org/10.1016/j.socscimed.2012.02.011

Parker Fiebelkorn, A., Person, B., Quick, R.E., Vindigni, S.M., Jhung, M., Bowen, A., Riley, P.L., 2012b. Systematic review of behavior change research on point-of-use water treatment interventions in countries categorized as low- to medium-development on the human development index. Social Science & Medicine 75, 622–633. https://doi.org/10.1016/j.socscimed.2012.02.011

Pickering, A.J., Crider, Y., Amin, N., Bauza, V., Unicomb, L., Davis, J., Luby, S.P., 2015. Differences in Field Effectiveness and Adoption between a Novel Automated Chlorination System and Household Manual Chlorination of Drinking Water in Dhaka, Bangladesh: A Randomized Controlled Trial. PLOS ONE 10. https://doi.org/10.1371/journal.pone.0118397

Prapas, D.E., Norton, B., Probert, S.D., 1987. Optics of Parabolic-trough, Solar-energy Collectors, Possessing Small Concentration Ratios. Solar Energy 39, 541–550.

Rainey, R.C., Harding, A.K., 2005. Drinking water quality and solar disinfection: Effectiveness in peri-urban households in Nepal. Journal of Water and Health 3, 239–248. https://doi.org/10.2166/wh.2005.036

Reygadas, F., Gruber, J.S., Ray, I., Nelson, K.L., 2015. Field efficacy evaluation and post-treatment contamination risk assessment of an ultraviolet disinfection and safe storage system. Water Research 85, 74–84. https://doi.org/10.1016/j.watres.2015.08.013

Rijal, G.K., Fujioka, R.S., 2001. Synergistic effect of solar radiation and solar heating to disinfect drinking water sources. Water science and technology : a journal of the International Association on Water Pollution Research 43, 155–162.

Rochelle, P.A., Marshall, M.M., Mead, J.R., Johnson, A.M., Korich, D.G., Rosen, J.S., De Leon, R., 2002. Comparison of in vitro Cell Culture and a Mouse Assay for Measuring Infectivity of Cryptosporidium parvum. Applied and Environmental Microbiology 68, 3809–17. https://doi.org/10.1128/AEM.68.8.3809-3817.2002

Rosenberg, D.E., Talozi, S., Lund, J.R., 2008. Intermittent water supplies: challenges and opportunities for residential water users in Jordan. Water International 33, 488–504. https://doi.org/10.1080/02508060802474574

Sachs, J.D., Mellinger, A.D., Gallup, J.L., 2001. The geography of poverty and wealth - Scientific American 284, 70–75.

Sandec, E., 2002. Solar water disinfection: a guide for the application of sodis, in: SANDEC Report No 06/02. EAWAG SANDEC Duebendorf, Switzerland.

Schulz, C.R., Okun, D.A., 1983. Treating surface waters for communities in developing countries. Journal - American Water Works Association 75, 212–219. https://doi.org/10.1002/j.1551-8833.1983.tb05119.x

Sikder, M., Mirindi, P., String, G., Lantagne, D., 2020. Delivering Drinking Water by Truck in Humanitarian Contexts: Results from Mixed-Methods Evaluations in the Democratic Republic of the Congo and Bangladesh. Environ. Sci. Technol. 54, 5041–5050. https://doi.org/10.1021/acs.est.9b07375

Sobsey, M.D., Stauber, C.E., Casanova, L.M., Brown, J.M., Elliott, M.A., 2008. Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. Environmental Science and Technology 42, 4261–4267. https://doi.org/10.1021/es702746n

Ssozi-Mugarura, F., Blake, E., Rivett, U., 2017. Codesigning with communities to support rural water management in Uganda. CoDesign 13, 110–126. https://doi.org/10.1080/15710882.2017.1310904

Stine, W.B., Geyer, M., 2001. Concentrating Collectors, in: Power From The Sun.

Su, Riffat, Pei, 2012. Comparative Study on Annual Solar Energy Collection of a Novel Lens-walled Compound Parabolic Concentrator (Lens-walled CPC). Sustainable Cities and Society 4, 35–40.

Sukkasi, S., Akamphon, S., 2013. Heat-transfer modeling as a design tool for improving solar water disinfection (SODIS) containers. Clean Technologies and Environmental Policy 16, 1773–1780. https://doi.org/10.1007/s10098-013-0689-0

Treacy, J., 2019. Drinking Water Treatment and Challenges in Developing Countries, in: Potgieter, N., Ndama Traore Hoffman, A. (Eds.), The Relevance of Hygiene to Health in Developing Countries. IntechOpen. https://doi.org/10.5772/intechopen.80780

Trip, R., Kuik, D.J., Westerweel, J., Poelma, C., 2012. An experimental study of transitional pulsatile pipe flow. Physics of Fluids 24. https://doi.org/10.1063/1.3673611

Troschinetz, A.M., Mihelcic, J.R., 2009. Sustainable recycling of municipal solid waste in developing countries. Waste Management 29, 915–923. https://doi.org/10.1016/j.wasman.2008.04.016

Ubomba-Jaswa, E., Fernández-Ibáñez, P., Navntoft, C., Inmaculada Polo-Lópezb, M., McGuigan, K.G., 2010. Investigating the Microbial Inactivation Efficiency of a 25 L Batch Solar Disinfection (SODIS) Reactor Enhanced with a Compound Parabolic Collector (CPC) for Household Use. Journal of Chemical Technology and Biotechnology 85, 1028–1037.

Ubomba-Jaswa, E., Navntoft, C., Polo-López, M.I., Fernandez-Ibañez, P., McGuigan, K.G., 2009. Solar disinfection of drinking water (SODIS): an investigation of the effect of UV-A dose on inactivation efficiency. Photochemical & Photobiological Sciences 8, 587–595. https://doi.org/10.1039/b817396f

UNICEF/WHO, 2019. Progress on household drinking water, sanitation and hygiene 2000-2017 Special Focus on Inequalities.

UNICEF/WHO, 2011. Drinking Water Equity, Safety and Sustainability, JMP Thematic Report on Drinking Water.

United Nations, 2018. The Sustainable Development Goals Report 2018. New York.

United Nations, 2012. Indicators for Monitoring the Millenium Development Goals: Definition and Methods of Computation [WWW Document]. URL http://mdgs.un.org/unsd/mi/wiki/7-8-Proportion-of-population-using-an-improved-drinking-water-source.ashx#p2

United Nations, 2010. General Assembly resolution 64/292, The human right to water and sanitation.

United Nations Committee for Development Policy, 2020. Outcome of the comprehensive review of the LDC criteria.

United Nations Environment Programme, 2019. GEO-6 - Global Environment Outlook.

USEPA, 2011. National Characteristics of Drinking Water Systems: Serving 10,000 or Fewer People. Water.

Varghese, A., 2004. A Comparative Risk Approach to Assessing Point-of-Use Water Treatment Systems in Developing Countries. Comparative Risk Assessment and Environmental Decision Making 99–112.

VIQUA, n.d. Ultraviolet Water Disinfection Systems from VIQUA.

Waddington, H., Snilstveit, B., White, H., Fewtrell, L., 2009. Water, sanitation and hygiene interventions to combat childhood diarrhoea in developing countries. International Initiative for Impact Evaluation.

Wang, X., Gao, W., Slusser, J.R., Davis, J., Olson, B., Janssen, S., Janson, G., Durham, B., Tree, R., Deike, R., 2008. USDA UV-B Monitoring System: An Application of Centralized Architecture. Computers and Electronics in Agriculture 64, 326–332.

WASREB, 2019. A Performance Report of Kenya's Water Services Sector - 2017/18, Impact: A Performance Report of Kenya's Water Services Sector – 2017/18.

Wegelin, M., Canonica, S., Alder, C., Marazuela, D., Suter, M.J.F., Bucheli, T.D., Haefliger, O.P., Zenobi, R., McGuigan, K.G., Kelly, M.T., Ibrahim, P., Larroque, M., 2001. Does sunlight change the material and content of polyethylene terephthalate (pet) bottles? Journal of Water Supply: Research and Technology - AQUA 50, 125–133. https://doi.org/10.2166/aqua.2001.0012

Welford, W.T., Winston, R., 1978. Optics of nonimaging concentrators. Light and solar energy. Academic Press Incorporated,New York, NY, United States.

Whelton, P.A., Dietrich, A.M., Burlingame, G.A., Schechs, M., Duncan, S.E., 2007. Minerals in drinking water: Impacts on taste and importance to consumer health. Water Science and Technology 55, 283–291. https://doi.org/10.2166/wst.2007.190

Whittington, D., Okorafor, A., Okore, A., McPhail, A., 1990. Strategy for cost recovery in the rural water sector: A case study of Nsukka District, Anambra State, Nigeria. Water Resources Research 26, 1899–1913. https://doi.org/10.1029/WR026i009p01899

WHO, 2015. Water-related diseases. WHO.

WHO/UNICEF, 2015. 25 YEARS Progress on Sanitation and Drinking Water: 2015 Update and MDG Assessment. New York, NY: UNICEF and World Health Organisation 4.

Wilson, D.C., 2007. Development drivers for waste management. Waste Management and Research 25, 198–207. https://doi.org/10.1177/0734242X07079149

Wingert, K., Zachary, D.A., Fox, M., Gittelsohn, J., Surkan, P.J., 2014. Child as change agent. The potential of children to increase healthy food purchasing. Appetite 81, 330–336. https://doi.org/10.1016/j.appet.2014.06.104

Wright, N.C., Winter, A.G., 2014. Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India. Desalination 352, 82–91. https://doi.org/10.1016/j.desal.2014.07.035

Yan, X., Ward, S., Butler, D., Daly, B., 2018. Performance assessment and life cycle analysis of potable water production from harvested rainwater by a decentralized system. Journal of Cleaner Production 172, 2167–2173. https://doi.org/10.1016/j.jclepro.2017.11.198

Yu, X., Su, Y., Zheng, H., Riffat, S., 2014. A Study on Use of Miniature Dielectric Compound Parabolic Concentrator (dCPC) for Daylighting Control Application. Building and Environment 74, 75–85.