An analysis of the time to disinfection and the source water and environmental challenges to implementing a solar disinfection technology (SolAgua)

by

Melinda M. Foran

A Thesis Submitted to the Faculty of the
Department of Population and International Health
Harvard School of Public Health
in Partial Fulfillment of the Requirements
for the Degree of Masters of Science
Boston, Massachusetts

May, 2007

This thesis has been read and approved by:

_____

Majid Ezzati
Associate Professor of International Health
Harvard School of Public Health
Thesis Supervisor

_____

Susan Murcott
Senior Lecturer
Massachusetts Institute of Technology
Second Reader

Acknowledgements

I wish to thank my thesis advisor, Majid Ezzati, for what has been a formative experience in my professional career. I appreciate your advice, candor, availability and skills at guiding me through a challenging process for a first-time researcher. I'm proud of the document that has developed over the past months and I know that I have you to thank for it.

To my second reader, Susan Murcott, it was such a pleasure working on the Pure Home Water project. Thank you for allowing me to become part of the Ghana team. You gave me the guidance I needed while allowing me to formulate my own research questions and conduct that research independently. I am so thankful for your support- both in the realm of laboratory supplies, laboratory space, and sage advice.

Xanat Flores and Alfinio Flores- thank you so much for producing SolAgua bags for my research and spending time explaining the genesis and development of the product. I feel privileged that I was the one of the first individuals to be able to give you evidence of microbial disinfection to help inform your future work. I wish you the best in the development and implementation of SolAgua.

On that note, the Pure Home Water network, especially Hamdiyah Alhassan and Wahab Salifu, supported me in my daily field work and were such a pleasure to know and work with. World Vision in Savelugu provided me not only desperately needed distilled water, but a place to conduct my field work, which was much appreciated.

To my support network at HSPH- Anna, Hirshini, Julia, Kate, Laura, and Maya- you have encouraged me when I needed it and challenged me to become a better researcher.

I had the pleasure of having two editors for this thesis, Rachel Schachter and Jacque Caglia. Thank you for spending hours of your personal time reading and improving my document.

Finally, I wish to thank my family- Mom, Megan, and Shawn- for what has truly been almost a year of growth and perseverance. I want to dedicate this document to my father, William. I know that he would have been proud of the culmination of all my hard work.

Abstract

This thesis investigated the potential of SolAgua, a solar water bag, to remove microbial contamination over a period of four hours and the role of environmental variables such as sunny versus cloudy conditions and source water conditions. The potential of SolAgua to remove microbial contamination was testing the current recommendation of exposing SolAgua to a minimum of two hours and a maximum of four hours to solar radiation. Field and laboratory tests explored the reduction in microbial contamination of SolAgua over a period of four hours of solar exposure. The field and laboratory studies concluded that SolAgua disinfection was able to achieve a high reduction (>99.0%) in the microbial indicator organisms of interest, total coliforms and *E. coli*, after four hours of exposure to sunlight in the field investigation and four hours of exposure to "sunny" conditions created using a 365nm wavelength UV lamp in the laboratory investigation. "Cloudy" conditions in the laboratory achieved a moderate reduction in total coliforms (95.6%) and *E. coli* (99.0%). Given the findings in this study, the SolAgua exposure recommendation of 2-4 hours should be changed to a minimum of four hours on sunny days and a maximum of one complete day of sunlight exposure on cloudy or overcast days until further studies can be completed. These results were then combined with observations from the field study to provide Pure Home Water, a non-profit social enterprise operating in the Northern Region of Ghana, with recommendations for SolAgua implementation.

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1. Introduction

1.1 Global Water Situation

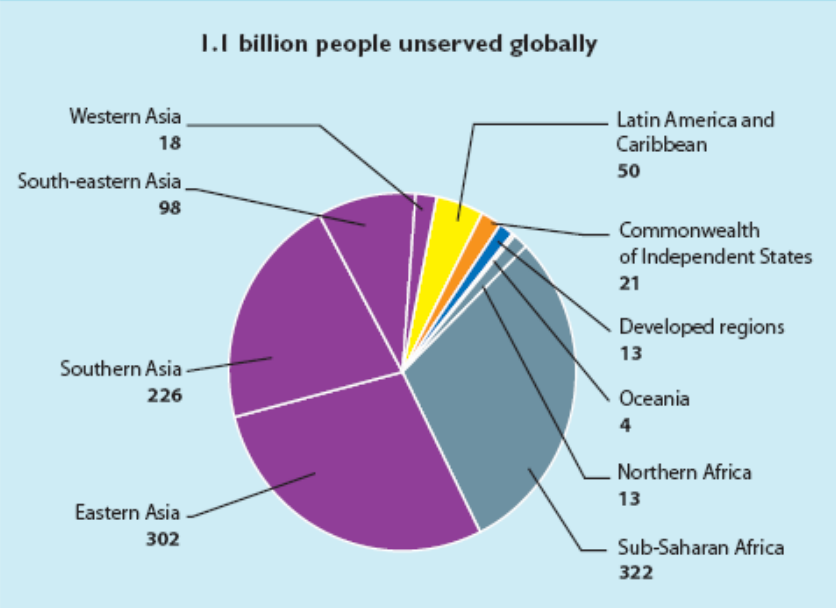
The World Health Organization (WHO) estimates that at least 1.6 million people die from diarrhea and hygiene related illnesses every year. These deaths are largely attributed to lack of access to safe drinking water and sanitation, as well as poor hygiene behaviors (WHO/UNICEF, 2006). Most people become sick with diarrheal disease through the fecal-oral transmission route, when fecal material is ingested by an individual (Cairncross & Feachem, 1996). Fecal-oral pathogens include a variety of living organisms including bacteria, protozoan, helminths, and viruses (Cairncross & Feachem, 1996), and they cause disease through multiple pathogeneses (*Control of Communicable Diseases Manual*, 2004). The fecal-oral route includes diseases that are waterborne, the pathogen is drunk by the individual, and water-washed, hygiene related (person-to-person) transfer of the pathogen to the mouth by the individual (Feachem, 1983).

Pathogenic agents often cause diarrhea, a symptom of gastrointestinal infection, which is defined as loose or frequent stools that may or may not be watery or contain blood. Diarrhea causes a loss of fluids which affects the adsorption of nutrients and can result in dehydration, a condition that can be life threatening for young children. Children with poor nutritional status can experience a vicious cycle whereby diarrhea causes poor growth through poor adsorption of nutrients and further reduces their resistance to infection making them more susceptible to diarrheal disease (WHO, 2007b).

To reduce morbidity and mortality from diarrheal disease, interventions aimed at improving access to clean water, sanitation and hygiene are implemented throughout the developed and developing world. Fecal contamination of water sources from animals or humans can create a water source that is unsafe for drinking without some form of water treatment or disinfection method. In an effort to distinguish between water sources of better water quality, improved and unimproved water sources have been defined, assuming that by being classified as an improved water source it is likely to be of better microbiological and sanitary quality than those that are unimproved. Improved water sources include household connections, public standpipes, boreholes, protected dug wells, protected springs, and rainwater collection. Unprotected wells, unprotected springs, rivers, ponds, vendor-provided water, bottled-water, and tanker truck water are all considered to be unimproved water sources under this classification system (WHO/UNICEF, 2004).

Using these measures, the WHO approximates that 1.1 billion people who do not have access to improved water sources and 2.6 billion people do not have access to sanitation (WHO/UNICEF, 2006). 42% of the population of sub-Saharan Africa is currently using an unimproved water source; however, the largest population without access to an improved drinking water source lives in South and East Asia- 528 million people (Figure 1) (WHO/UNICEF, 2006).

Figure 1: Population without Access to Improved Drinking Water Sources by 2004 (in millions)



Source: WHO/UNICEF (2006)

Several studies have sought to quantify the burden of disease from poor access to safe drinking water, the most prominent of which is the Global Burden of Disease (GBD) study. The 2001 GBD estimates for the overall burden of disease due to poor access to water, sanitation, and hygiene has been calculated at 4.0% of all deaths worldwide. In addition, water, sanitation and hygiene account for 4 billion cases of diarrhea and 5.7% of disability-adjusted life years (DALYs) in the world population (Pruss, Kay, Fewtrell, & Bartram, 2002). DALYs are an aggregate measure of population health that quantify the number of years lost due to morbidity and mortality attributed to specific diseases (*The Global Burden of Disease*, 1996), in this case due to water, sanitation, and hygiene-related disease. The majority of mortality and morbidity from water, sanitation and hygiene related conditions occur in children under the age of five (Thompson & Khan, 2003).

Furthermore, in low and middle income countries, diarrheal disease is the seventh leading cause of death, following ischemic hearth disease, stroke, lower respiratory infections, HIV/AIDS, perinatal conditions, and chronic obstructive pulmonary disease. Globally, diarrheal disease is also the sixth leading cause of premature death. Unsafe water, sanitation and hygiene account for 3.7% of the disease burden (mortality and morbidity) in low and middle income countries, slightly more than the burden from indoor smoke due to the burning of solid fuels in the home which accounts for 3% of the global burden (Lopez, Mathers, Ezzati, Jamison, & Murray, 2006).

The current policy agenda to improve access to safe water is outlined in the Millennium Development Goals (MDGs), adopted by 189 member states of the United Nations in the year 2000. The MDG for water aims, "By 2015 to reduce by one-half the proportion of people without sustainable access to adequate quantities of affordable and safe water" (WHO/UNICEF, 2004). There are regions of the world, such as South Asia, making substantial progress towards meeting the MDG for safe water. Sub-Saharan Africa, however, is not on schedule to meet the target. Although access to safe water has increased from 49% to 58% of the population in Sub-Saharan Africa from 1990 to 2002, the region has not made enough progress to meet the goal of 75% of the population by 2015 (WHO/UNICEF, 2004).

Over 500 million people in the world will be left without access to an improved water source, even if the MDG for water is achieved. There remains an urgent need to meet the safe water demands of this population. To meet this need, the WHO aims to reach this population through improved access to safe water storage and treatment at the household level (Sobsey, 2002).

1.2 Point-of-Use Water Treatment

While it is important to increase access to improved water sources, the assumption that improved sources of water are of higher microbial quality does not necessarily hold true after the water has been transported and stored in the home. For example, there are opportunities between the water source and the household for the water to become re-contaminated through contact with unwashed hands, further perpetuating the cycle of poor quality drinking water. Household storage containers often allow for recontamination when water is removed using a cup through the opening at the top of the storage container, be it a traditional clay pot or a plastic bucket.

In an investigation of point-of-use water quality from both unimproved and improved sources, Clasen and Bastable showed that microbiological water quality, specifically fecal contamination, was found at the point of consumption in water from both types of sources. In 75.6% of samples from improved water sources, there were levels of fecal coliform that exceeded the recommendations set forth by the Sphere Standards for use during humanitarian crises and emergencies at the point-of-use (T. F. Clasen & Bastable, 2003).

These opportunities for re-contamination can be averted through modern water treatment methods of clarification, sedimentation, and disinfection with centralized, piped water systems. With current trends, these systems are unlikely to be disseminated throughout much of the developing world for some time. There is a pressing need to bridge the gap between water that is safe at the source and water that is safe at the point of consumption, whether the point of consumption is at home or away from home. As was shown by Clasen and Bastable in 2003, these efforts may primarily benefit those who do not have access to improved water sources. There may also be a benefit to people who have access to an improved water source but face a potential point- of-use health risk during water transportation or storage.

In a paper outlining household water treatment technologies, Murcott describes three broad areas of water quality- physical, chemical and microbiological- that can be improved by household water treatment technologies. Physical removal technologies include ceramic and biosand filters, cloth filters, and coagulation/flocculation technologies. Boiling, solar disinfection (SODIS), chlorination, and UV irradiation with lamps are examples of technologies that improve the microbiological quality of the water. Improving the chemical water quality of source waters may require special measures at the household level, but can be achieved with charcoal or hybrid adsorption with carbon. There are also technologies that combine multiple methods to achieve improved water quality, for example, partnering coagulation and flocculation with a disinfection technology such as chlorination. Finally, safe storage containers should be designed using a standard size storage vessel, with a narrow mouth or opening with a lid and an easily accessible tap to dispense the water (Murcott, 2006).

To demonstrate the ability of HWTS technologies to improve human health, several meta-analyses have been conducted to examine the variety of empirical evidence from the field. Interventions aimed at improving water quality, such as household water treatment and safe storage (HWTS) technologies, have been shown to reduce diarrheal disease on average by 39% (Fewtrell et al., 2005).

A more recent meta-analysis, conducted by Clasen et al., to assess the effectiveness of interventions that improve water quality has concluded that point-of-use interventions are more effective at reducing diarrhea in all age groups than interventions that improve water quality at the source (T. Clasen, Roberts, Rabie, Schmidt, & Cairncross, 2006). Point-of-use treatment interventions have been shown to significantly reduce diarrheal disease (Chiller et al., 2006; T. F. Clasen, Brown, Collin, Suntura, & Cairncross, 2004; Nath, Bloomfield, & Jones, 2006; Quick et al., 2002; Quick et al., 1999).

The effectiveness of individual point-of-use technologies is assessed through meeting water quality targets for pathogen reduction. Currently, a highly effective technology will reduce more than 99% of the pathogens, a moderately effective technology reduces pathogens by between 90% and 99%, and a technology that has low effectiveness only reduces pathogens by less than 90% (Sobsey, 2002).

The advantage of point-of-use technologies is that they are low-cost and can be implemented relatively easily in low resource settings. Point-of-use interventions are often combined with education and behavior modification campaigns to increase knowledge of waterborne disease and the pathways by which people become sick (Sobsey, 2002). There remain a variety of considerations that need to be analyzed when determining the ability of a particular HWTS technology to be successful, particularly: simplicity, accessibility, cost, socio-cultural acceptability, sustainability and potential for dissemination (Sobsey, 2002).

1.3 Solar Disinfection

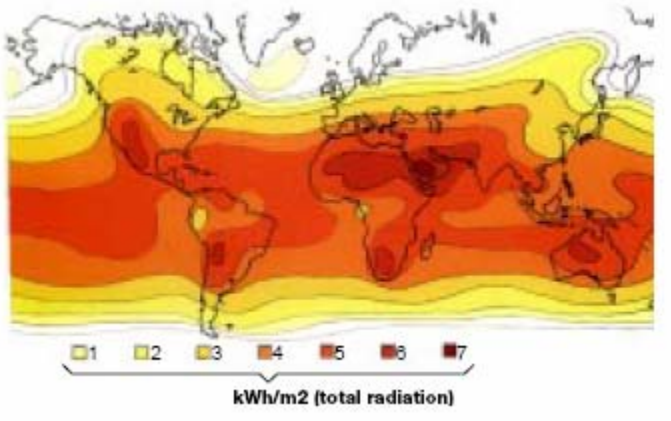
This section gives a short overview of solar disinfection, reviews the most relevant studies for this thesis paper, quantifies the potential public health impact of a solar disinfection intervention, describes the technology to be studied (SolAgua), and discusses potential limitations of SolAgua disinfection.

1.3.1 Solar Disinfection Overview

The solar disinfection method that has come to be known as SODIS has been researched and implemented over the past 25 years. The user fills a polyethylene terephthalate (PET) plastic water bottle with 1-2 liters of water, shakes the bottle to aerate the water and places the bottle on a roof or sheet of corrugated metal. The bottles are exposed for an entire day of direct sunlight (at least six hours). If it is a cloudy day, then it is recommended that the bottle be exposed for two days of sunlight. The result is safe drinking water of high microbiological quality, free of pathogens (EAWAG/SANDEC, 2002).

SODIS inactivates pathogens through two mechanisms: the absorption of ultraviolet (UV) rays in the range of 320-400 nanometer (nm) wavelength (UV-A) by pathogen DNA and heat created through exposure to solar energy. Heat is created when the PET plastic bottles are exposed to sunlight, both a function of the ambient temperature and the solar radiation absorbed by the bottle. The combined germicidal effect of UV-A radiation and heat kill waterborne microbial contaminants in the water. The most appropriate region for the application of SODIS is semi-arid and arid regions between latitudes 35°N and 35°S. Figure 2 illustrates the areas of the world that experience the most solar radiation. The more red/orange the region, the more appropriate the area is for the application of solar disinfection (EAWAG/SANDEC, 2002).

Figure 2: Global Solar Energy Distribution



Source: EAWAG/SANDEC (2002)

1.3.2 Solar Disinfection Limitations

There are several limitations to SODIS as a household water treatment technology. It is not appropriate for disinfecting large quantities of water given that it is performed in 1-2 liter bottles or bags. It is most appropriate to disinfect enough water for drinking at the household level. SODIS does not remove chemical contamination nor does it change the odor of the source water. Finally, solar disinfection requires source water that is not very turbid (EAWAG/SANDEC, 2002). Turbidity is defined as "insoluble particulates that impede the passage of light through water by scattering and absorbing rays" (Viessman, 1998) and is measured in nephelometric turbidity units (NTU) with a turbidimeter. Organic matter and suspended silt typically comprise the particulate matter that causes light to be scattered and absorbed (Viessman, 1998), which prevent UV radiation from penetrating the water, inhibiting the inactivation of pathogens. Several studies have confirmed that SODIS performed in bags or bottles should only be performed on source waters that are less than 30 NTU (EAWAG/SANDEC, 2002; Sobsey, 2002).

1.3.3 Development of Solar Disinfection

The development of solar disinfection began when researchers were searching for an inexpensive method of disinfecting water for the addition of oral rehydration salts. The first solar disinfection experiments were conducted in the early 1980's by Acra, et al. and showed that inactivation of pathogens was occurring primarily due to exposure to UV-A radiation (320-400 nanometer (nm) wavelength) and to a lesser degree from UV-B radiation (400-490nm wavelength) (Acra, Raffoul, & Karahagopian, 1984).

The development of SODIS in PET plastic bottles was studied in the early 1990's as a low-cost method for household water treatment. The Swiss Federal Institute for Environmental Science and Technology (EAWAG) conducted laboratory and field tests confirming that solar energy could be used at the household level to produce high-quality drinking water (EAWAG/SANDEC, 2002). To expand the empirical evidence supporting the effectiveness of SODIS, Wegelin and colleagues confirmed that exposure to solar radiation in the 350-450nm wavelength range reduced *Escherichia coli* (*E. coli*) by 3-log. The experiments in the lab concluded that the fluence necessary for a 3-log reduction of *E. coli* was approximately 555 W•h/m^2 and corresponded to 5 hours of mid-latitude sunshine during the summer months. The authors noted a synergistic effect between the UV radiation and the increase in temperature created through exposure to solar energy. Inactivation of

bacteria increases steadily as temperature increases from 20°C to 50°C and at temperatures above 50°C there is a significant increase in the inactivation of pathogens (Wegelin, 1994).

Further studies were conducted in the field to assess SODIS' application at the household level. McGuigan, et al. completed a SODIS field study in Kenya and confirmed that synergistic effects between thermal energy and UV radiation occurred at temperatures greater than 45°C. The researchers also concluded that inactivation of *E. coli* from UV radiation occurred even with turbid water sources of as much as 200 NTU provided the source water achieved a temperature of more than 55°C (McGuigan, Joyce, Conroy, Gillespie, & Elmore-Meegan, 1998). This study was able to demonstrate that SODIS was an applicable, low-cost household water treatment method.

1.3.4 Public Health Impact

Although substantial evidence supported the ability of solar disinfection to be a successful household water treatment technology, there was still a need to connect the microbiological reduction with public health impact in the population and most importantly, children given their susceptibility to diarrheal disease. A randomized control trial assigned Maasai children aged 5 to 16 in Kenya to either the control group, who placed PET plastic bottles full of water in the dark within their homes, or to the intervention group, who placed PET plastic bottles full of water on the roof of their homes during daylight hours for the duration of the day. After twelve weeks, the intervention group showed a significant reduction diarrheal morbidity in children aged 5 to 16. The investigators found a 10% reduction in incidence of all diarrhea episodes and a 24% reduction in incidence of severe cases of diarrhea (Conroy, Elmore-Meegan, Joyce, McGuigan, & Barnes, 1996).

Children aged 5 and under are the most susceptible to diarrheal disease morbidity and mortality. In order to find empirical evidence to support the reduction of diarrheal disease morbidity in young children, a randomized control trial, a follow-up to the previous study, was conducted among households with children under the age of 6 in Kenya. The results showed that children who consumed SODIS water had a significantly lower risk of severe diarrheal disease and overall a moderate reduction in all diarrheal disease- 9.3% reduction (Conroy, Meegan, Joyce, McGuigan, & Barnes, 1999). The advantage of this study was that the results were sustained over a period of one year, despite only a moderate reduction in diarrheal disease morbidity.

There was an outbreak of cholera in the community shortly after the randomized control trial concluded. Conroy and colleagues investigated if there was a difference between cases of cholera in children under the age of 5 within the study population. There were significantly less cases of cholera in children aged 5 and under (3 out of 155 children) in the group drinking SODIS water compared to the control group (20 out of 144 children), demonstrating the ability of SODIS to reduce cholera disease by 86% (Conroy, Meegan, Joyce, McGuigan, & Barnes, 2001) and its potential use during emergency and disaster situations.

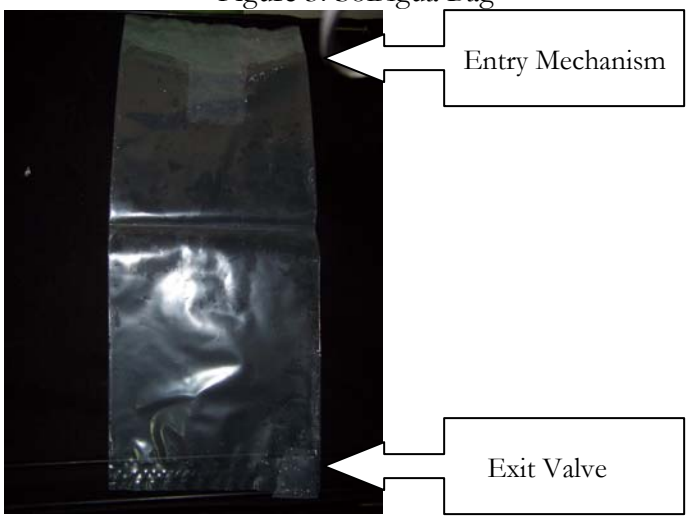
These studies showed that SODIS in PET plastic bottles was effective at reducing diarrheal morbidity in children and established evidence for organizations to develop and implement solar disinfection projects to improve household water quality and health.

1.3.5 SolAgua

SolAgua was developed in 2005 by a team of students from the Massachusetts Institute of Technology Development Laboratory (D-Lab), an undergraduate course aimed at designing

technologies to respond to the basic needs of low-income households in the developing world. Through coursework the team created a simple water bag that can be manufactured from a single sheet of plastic. The water bag, subsequently named SolAgua, has an entry mechanism at the top to pour the water into the bag and then a small valve at the bottom which folds underneath a lip to provide a safe way to empty the water without recontamination. If SolAgua is inverted, the entry mechanism closes so that water is not able to escape through the top of the bag (Figure 3).

Figure 3: SolAgua Bag

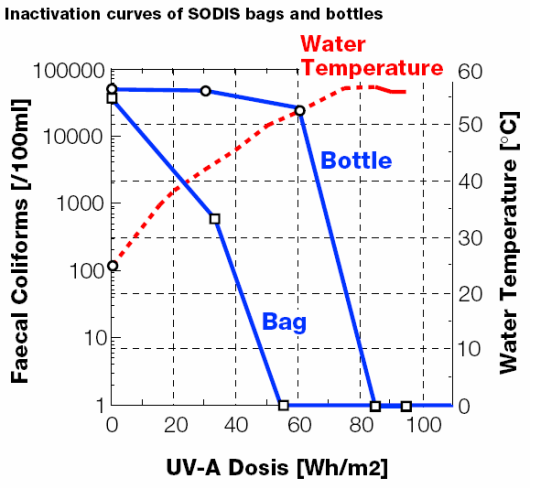


Source: Foran (2006)

The current design holds approximately 2 liters of water, but could be made larger or smaller depending on the demands of the community. There is an option to add a plastic handle for ease of carrying and use. The simple design can be made with locally available materials of plastic sheeting and a heat sealer to create the entry and exit valves. The manufacturing process requires little training, so local labor could be employed and the result would be a product that is inexpensive to manufacture and sell. Depending on the grade of plastic used, there is a trade off between penetration of the UV rays and durability. Stronger plastics will be more robust but pathogens will persist for a longer period of time thus requiring a longer exposure period.

SolAgua has a distinct advantage over a PET plastic bottle because it allows for a more efficient transfer of solar energy and consequently more efficient inactivation of pathogens. The shallow water depth in the SolAgua bag, as opposed to the bottle, allows for better penetration of the sun's rays because the depth of water is less in SolAgua than an entire PET plastic bottle. Illustrated in Figure 4, experiments conducted by EAWAG showed faster inactivation of fecal coliforms in a SODIS bag versus a SODIS PET plastic bottle with similar doses of UV-A radiation. Based on this evidence, the study team proposed that sun exposure of 2-4 hours would eliminate pathogens in the water. Prior to this thesis only limited field trials of SolAgua had taken place and this hypothesis was unsubstantiated by laboratory tests.

Figure 4: Inactivation of Fecal Coliforms with SODIS Bags and PET Plastic Bottles



Source: EAWAG/SANDEC (2002)

1.4 Research Questions

The purpose of this study is to use two investigations, one in the field and one in the laboratory, to identify the time to disinfection as it is affected by the variables of source water turbidity and solar radiation on sunny versus cloudy days. These two investigations aim to answer the following questions:

1. Does SolAgua achieve a high reduction (>99%) of microbial contamination in a low turbid (< 5 NTU) source water over a period of four hours?
2. Does SolAgua achieve a high reduction (>99%) of microbial contamination in a low turbid (< 5 NTU) source water during the recommended 2-4 hours of sunlight exposure for SolAgua under both "sunny" and "cloudy" conditions created in the laboratory?
3. Is SolAgua a viable household water treatment technology for the Northern Region of Ghana with respect to source water (highly turbid) and environmental conditions (solar radiation on both cloudy and sunny days)?

The first research question posed will be analyzed by both the field and laboratory studies. The reduction of microbial contamination by SolAgua disinfection was measured after four hours using a low turbid water sources from both the Northern Region and Boston, MA. This information will be connected to the second research question that further explores "cloudy" and "sunny" conditions under controlled laboratory conditions to test the current recommendation of a minimum of two hours and a maximum of four hours of solar exposure. More specifically, the laboratory experiments will measure the reduction of microbial contamination after 1, 2, 3 and 4 hours under two different UV-A radiation conditions. The current recommendation of 2-4 hours of exposure to sunlight does not take into consideration the variation of solar radiation under cloudy and sunny conditions; therefore, one goal of the laboratory tests is to provide the SolAgua team with a body of evidence that will either support or challenge the current recommendation. This will be determined by SolAgua's ability to remove more than 99.0% of microbial contamination.

Finally, this study will apply this knowledge of the reduction of microbial contamination over time using SolAgua to the mission and objectives of Pure Home Water in reaching their current target population with safe water. The source water turbidity and meteorological conditions in the Northern Region will be explored to support or challenge what has been discovered through the

microbial contamination testing. The goal of this analysis is to provide Pure Home Water with recommendations for application of solar disinfection technologies in the region, and further study SolAgua as an appropriate household water treatment technology.

2. SolAgua Field Study

2.1 Field Study Background

The background section provides context for the field study conducted in the Northern Region of Ghana. While the field study itself was not community based, these sections describe the current water situation in the Northern Region, demonstrate the need for point-of-use water treatment, highlight regional waterborne disease concerns that are relevant to SolAgua implementation, and explain the genesis of the SolAgua studies conducted for this thesis.

2.1.1 Northern Region of Ghana

Ghana has a population of over 22 million people (UNICEF, 2005) with 1.8 million living in the Northern Region (GSS, 2005). There are ten major regions in the country, shown in Figure 5. The Northern Region is divided into 13 different districts, including the regional capital of Tamale, the third largest city in the country (GSS, 2005).

Figure 5: Regions and Major Cities of Ghana

Source: VanCalcar (2006)

The infant mortality rate in Ghana is 64 deaths per 1,000 live births and the under-five mortality rate is 111 per 1,000 live births (DHS, 2003). Average life expectancy is 57 years of age (UNICEF, 2005). These country-wide statistics do not reflect the difference between infant and child mortality in the Northern versus Southern regions. In the Northern Region, infant morality is 69/1,000 live births and under-five mortality is 154/1,000 live births. The Northern Region has the second highest under-five mortality rate after the Upper West region, and the third highest infant mortality rate behind the Upper West and Volta regions (DHS, 2003).

According to the Ghana Statistical Service, the prevalence of diarrhea in children under the age of five was 15.3% during the two weeks prior to a 2003 survey (VanCalcar, 2006). While this does not reflect incidence of diarrhea, prevalence is an indicator of poor access to water, sanitation and hygiene. Approximately 16% of the population has access to a piped supply within their home, yard, or plot, 23% have access to a public water tap, 12% use water from open wells, 28% use closed wells or boreholes, and 14% access water from rivers or streams (DHS, 2003). This indicates that over one-fifth of the population does not have access to an improved water source as classified by the WHO. The Demographic and Health Survey conducted in Ghana in 2003 estimated that only 2% of the rural population in Ghana had access to piped water within the home, yard or plot, and this percentage has remained constant over the past five years.

2.1.2 Guinea Worm

The presence of guinea worm in the Northern Region is a serious consideration for the application of any technology aimed at providing safe drinking water to the local population. *Dracunculiasis medinensis* or guinea worm is a debilitating waterborne disease that infects an individual through ingestion of copepods (fresh water fleas) that are infected with the guinea worm larvae. The larvae are released in the stomach where they reproduce and the female worm grows over a period of 10-14 months. The female worm, approximately 2-3 feet long, travels within the body, typically to the lower limbs. The female worm will cause a blister at the surface of the skin before breaking through the skin 24-72 hours after blister formation. When the individual seeks to relieve the pain by submerging his/her limb in the public water supply (pond or lake), the female worm releases larvae which are consumed by copepods and the cycle continues. The removal process may take weeks or months because the worm has to be removed from the body slowly, by wrapping it around a stick only extracting 2-3 centimeters per day otherwise the worm will break and the process will take longer (CDC, 2004).

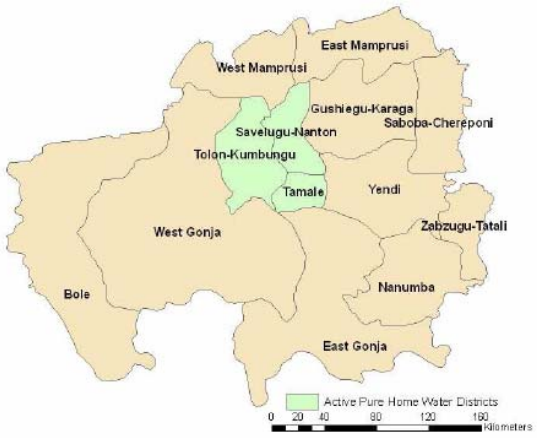
Guinea worm is endemic in only nine countries in the world, all located in Africa. The distribution of guinea worm cases is largely restricted to two countries: Sudan and Ghana. Ghana experienced a 4% increase in reported cases of guinea worm from 2005 to 2006, reporting at total of 4,132 cases in 2006. 90% of those cases were reported in the Northern Region of Ghana (CDC, 2007a). In the month of January, 2007 the district of Savelugu-Nanton reported 1,189 cases of guinea worm, which officials are attributing to a breakdown in the municipal water supply during January, 2006. Residents of the district bought contaminated water; leading to the increase in cases one year later (CDC, 2007b). There is a need for improved water supply in the Northern Region and/or a reliable household water treatment method for the population.

2.1.3 Pure Home Water

Pure Home Water (PHW) is a non-profit social enterprise located in the Northern Region capital of Ghana, Tamale, with the goal of improving access to safe drinking water through the sale of

household water treatment technologies and safe storage products, specifically focusing on the promotion and dissemination of the Ceramic "Potters for Peace" Filtron filter. Founded in 2005, PHW targets three districts in the Northern Region- Savelugu-Nanton, Tolon-Kumbungu and Tamale proper (Figure 6)- and aims to bridge the gap between water supply projects and safe drinking water in the home (Alhassan & Salifu, 2006).

Figure 6: Districts of the Northern Region



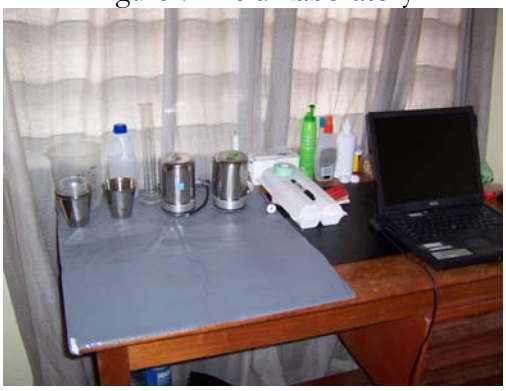
Source: VanCalcar (2006)

Through technical assistance from business and engineering masters students, PHW identified that the current price of the ceramic water filter was too high for the poor in the region, which account for 69% of the population in the Northern Region (IPC/UNDP, 2004). There was a strong need to investigate other HWTS technologies that were socially acceptable, low-cost, and appropriate for the region. To meet this need, the author of this paper and the project team wanted to study the feasibility of a solar disinfection product to provide safe drinking water for the local population.

2.2 Field Study Design & Methods

Field work was conducted in the Northern Region of Ghana within and around the town of Tamale during the months of June and July, 2006. Eleven field tests were performed in order to better understand how SolAgua performed under the meteorological conditions in the Northern Region. Figure 7 shows the field laboratory used for microbial contamination testing, which is explained in more detail in section 2.2.5.

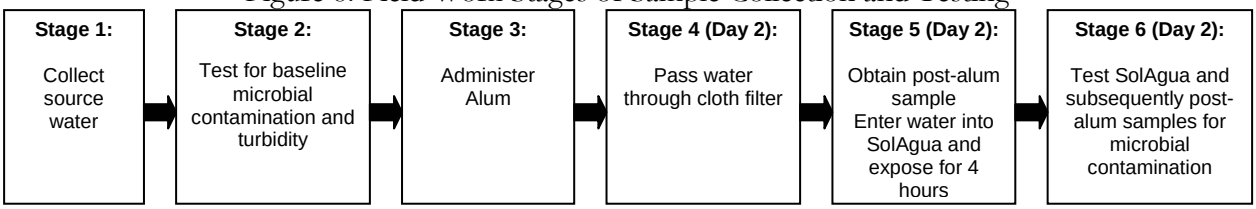
Figure 7: Field Laboratory



Source: Foran (2006)

The procedures for field sample collection and testing for microbial contamination are outlined in Figure 8 and described in more detail in the subsequent sections.

Figure 8: Field Work Stages of Sample Collection and Testing



2.2.1 Source Water

With the guidance of PHW employees, source waters were selected on the basis of whether or not local households used the water specifically for drinking. In this case, all source waters were local dams, which are dugouts or man-made ponds that collect water during the rainy season. Some of the water sources are available year-round while others dry up during the dry season between November and April. All samples were collected during the rainy season.

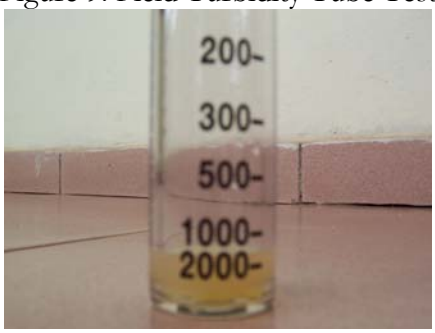
Source water was collected using a 2.5 gallon bucket and three, pre-sterilized 125ml Whirl-Pak® bags. The 2.5 gallon bucket was rinsed several times with the source water and then filled to the top. The Whirl-Pak® bags were filled using the water from the 2.5 gallon bucket and then inserted into an insulated carrying bag with an ice pack to maintain baseline water contamination levels during transport to the field laboratory. All samples arrived at the lab approximately 1 hour after collection, well within the 4-6 hour recommended timeline.

2.2.2 Turbidity

Turbidity is a critical property of the source water insofar as it affects the achievement of efficient inactivation of microorganisms. A turbidimeter was not available on-site; therefore, a turbidity tube measuring turbidity units (TU) was used as a proxy for NTU. A turbidity tube is not as precise as a turbidimeter at turbidities less than 5 TU (WHO, 2007a), however, since past solar disinfection studies have recommended that the turbidity of source water measure no more than 30 NTU (EAWAG/SANDEC, 2002), this method of measuring turbidity had adequate precision to determine if the source water was too turbid for SolAgua disinfection.

The turbidity tube is used by pouring the well-mixed source water into the tube, looking down from the top of the tube, and determining when the bulls-eye at the bottom of the tube is no longer visible. Using an iterative process of addition and subtraction of source water from the tube, turbidity was measured by lining up the water level with pre-drawn lines on the side of the tube (Figure 9).

Figure 9: Field Turbidity Tube Test



Source: Foran (2006)

Since the dugouts and dams in the Northern Region are unlined pits that collect water during the rainy season and all samples were collected during the rainy season, the source waters contained high levels of turbidity. Figure 9 shows the level of source water taken from Ghanasco Muali Dam and the corresponding turbidity of approximately 1,600 TU, which greatly exceeds the recommended 30 TU. A conservative average of the turbidity of source waters sampled in the Northern Region was 690 TU.

2.2.3 Pre-Treatment Using Alum

To mitigate the problem of turbidity, a local solution was employed to pre-treat any sample that had a turbidity exceeding 30 TU. In the Northern Region of Ghana, alum, a commonly used coagulant and flocculent, was widely available in the market and used by local women to pre-treat very turbid dam water. Alum, aluminum sulfate, reacts with the natural alkalinity of water to create aluminum hydroxide floc which when agitated through stirring causes coagulation- the process by which chemicals are added to water so that particulates collect into clusters (Viessman, 1998). This was an expedient method to accelerate sedimentation of the particulates in the source water.

Figure 10: Alum Balls from Tamale Market and Alum Administration

Source: Foran (2006)

One alum ball was administered to each source water container and stirred for approximately three minutes to induce the reaction (Figure 10). All source water in this study had alum administered after returning to the field laboratory and testing for microbial contamination. The resultant mixture was left to settle overnight in order to take advantage of the strongest hours of solar energy the following day for the SolAgua experiments.

2.2.4 Cloth Filter

To remove any particles floating at the top of the source water the following day, a guinea worm cloth filter was used to filter out flocs of organic matter before SolAgua containers were filled. Cloth filters to remove guinea worm copepods are widely available and used in the Northern Region of Ghana because of the sustained guinea worm epidemic. Post-alum water was passed through this filter into a 1,000mL plastic beaker the morning after source water collection to remove any remaining particles before SolAgua disinfection was performed (Figure 11).

Figure 11: Guinea Worm Cloth Filter

Source: Foran (2006)

Two samples of water were extracted from this post-alum, cloth filtered water in order to investigate the reduction in microbial contamination after administering alum alone versus the administration of alum and SolAgua disinfection. The post-alum water samples were decanted from the plastic beaker and stored in 125ml Whirl-Pak® bags and tested from microbial contamination immediately after testing the SolAgua water for microbial contamination using the membrane filtration method described in section 2.2.5.

2.2.5 SolAgua Disinfection

SolAgua disinfection experiments were conducted the morning after source water collection in order to expose SolAgua bags during the strongest hours of solar energy. Each bag was filled with approximately 1.5-2 liters of water to maintain consistency between the tests. Ideally, bags would have been filled with 2 liters of water; however, the SolAgua bags were not durable enough and often had leaks along the sealed surfaces. This quantity of water in the SolAgua bags is comparable to SODIS performed in 2 liter PET plastic bottles, which provides a basis for comparing the time to disinfection of the two different solar disinfection technologies.

SolAgua bags were exposed to sunlight for four hours and then tested for microbial contamination. In Figure 12, Bipelar Dam water, both the original source water (left) and the alum treated water (right), was exposed to sunlight in SolAgua bags on the corrugated metal roof of the field laboratory.

Figure 12: SolAgua Disinfection with Bipelar Dam Water

Source: Foran (2006)

2.2.6 Microbial Contamination Indicator Organisms

There are several bacterial indicator organisms that can be used to measure fecal contamination of water. The indicator organisms chosen for this study were total coliforms and *E. coli*. Coliforms are naturally occurring in the environment and include both fecal coliforms (bacteria from human or warm-blooded animal feces) and coliform bacteria from feces that are not from humans or warm blooded animals, soil and other origins. The WHO recommends a standard of 0 total coliforms per 100mL immediately after disinfection because the presence of coliforms can be an indicator of fecal contamination (Viessman, 1998).

E. coli is included as a subset of total coliforms and is a much better indicator of fecal contamination since *E. coli* only comes from animal and human fecal waste (Viessman, 1998). According to studies conducted at the American University of Beirut in the early 1970's, *E. coli* is more resistant to the effects of sunlight than other bacteria such as *S. typhi, P. aerugenosa* and *S. enteritidis* (Acra, Raffoul, & Karahagopian, 1984), for that reason, *E. coli* was chosen as a good indicator organism to use for the purposes of this study. *E. coli* has been shown to indicate the inactivation of both bacteria and viruses, which is advantageous in monitoring the efficacy of solar disinfection (Wegelin, 1994). The drinking water standard recommended by the WHO for *E. coli* is 0 per 100mL (WHO, 2006).

2.2.5 Membrane Filtration Technique

There are several methods to determine microbial contamination of water, the first and most simple to perform being the Presence/Absence test which uses the presence of H_2S-producing microorganisms as a proxy for the presence or absence of coliform pathogens and has the ability to detect 1 CFU/100mL. This test, however, is not very sensitive in detecting fecal contamination because the presence of non-pathogenic, naturally occurring sources of H_2S in the water sample may react with iron (the active test ingredient) (Mattelet, 2006). This method was determined to be inadequate for this study.

The membrane filtration (MF) technique was used to establish levels of microbial contamination in both the field and laboratory experiments because this procedure enables enumeration of total coliforms and *E. coli* when using m-ColiBlue24® media. The MF procedure was more appropriate because it allowed for a more accurate recording of reduction in total coliforms and *E. coli* over time. A general methodology is outlined below and diversions from the methodology due to limitations in the field experiments are detailed in a subsequent section.

The MF method was performed using a Millipore field laboratory filter. The filter apparatus was first sterilized by pouring a cap-full of methanol onto the ceramic ring at the base, igniting the methanol and sealing the filter unit with the cup. The filter was allowed to sterilize for 15 minutes before proceeding with the unit setup.

To begin, 100ml of distilled water was run through the filter apparatus and then the vacuum pump was connected. A sterile petri dish with an absorbent pad was labeled and the m-ColiBlue24® culture media was added to the dish. Excess media was poured out of the petri dish, assuring that the absorbent pad was evenly soaked, leaving only a drop of media on the pad. A pre-packaged 0.45µm filter paper was aseptically removed from the package with sterile tweezers (which had been flame sterilized) and placed on top of the support base of the filter unit. The filter paper allowed particles smaller than 0.45µm to pass through the filter while capturing particles larger than 0.45µm, which include both of the bacterial indicator organisms of interest.

The filter unit was reassembled and 100mL of sample water was poured into the funnel, using a circular motion and not directly poured onto the filter paper. To avoid cross-contamination between samples and ensure an accurate number of indicator organisms, 30mL of distilled water was filtered three times after each 100mL sample. To remove the filter paper, the filter apparatus was disassembled and the paper was aseptically removed using sterile tweezers and placed onto the petri dish using a rolling motion to assure that no air bubbles were caught between the absorbent pad and the filter paper. Each petri dish was placed upside down inside the incubator at 35°C for the recommended 24 ± 2 hours.

When each petri dish was removed from the incubator the following day, the number of colony forming units (CFU) was counted using a magnifying glass. Since each sample tested measured 100mL, the total number of CFU is expressed per 100mL. Total coliforms are represented by red and blue colonies and *E. coli* are the blue colonies. To be assured of statistically valid colony counts, total bacterial colonies should count no more than 200 total colonies on the petri dish (Millipore). If the petri dish had more than 200 total colonies then they were recorded as too numerous to count (TNTC). The MF method has a sensitivity of 1 CFU/100mL. The source water used in both the field experiments had high numbers of total coliforms and *E. coli*, therefore, it was necessary to run and test several dilutions of the source water to ensure that the tests generated valid colony counts. All dilutions of source water and SolAgua water were made using distilled water obtained from the World Vision Water Quality Laboratory in Savelugu, Ghana for the field study and deionized, sterilized water for the laboratory study (Figure 13).

Figure 13: MF Tests – Dilutions
1:50, 1:75, 1:100, 1:200, 1:500, 1:1,000 (bottom from left to right) Two blank controls on the top

Source: Foran (2006)

Every petri dish that generated a valid colony count was averaged and this number was recorded as the baseline microbial contamination for the source water. At least three valid colony counts were averaged for each source water when measuring baseline microbial contamination, although as many as six dilutions were averaged on some occasions.

2.2.6 Field Limitations

There were several limitations encountered in the field, including a lack of methanol as well as time and sterilization constraints. To avoid contamination of samples, all dilutions of source water and samples taken from the post-alum and SolAgua water were mixed inside the pre-sterilized 125ml Whirl-Pak® bags. As a result, only the 100mL graduated cylinder needed to be sterilized, which was done by immersing the cylinder in boiling water for 10 minutes and then used promptly upon cooling.

Customarily, the filter unit is sterilized between tests; however, there was no methanol available in Tamale to properly sterilize the filter mechanism. Two methods were used in order to ensure that the tests were valid: filtering multiple dilutions of the same source water sample followed by a blank control and cleaning the filter funnel using alcohol between sample tests.

It was time consuming to sterilize the filter between sample tests; therefore, several dilutions of the same water sample were filtered where the most dilute was filtered first, followed by less dilute samples. Each series of tests using the same filter was followed by a control test where a 100mL sample of distilled water was filtered and tested in order to assure there was no cross contamination between samples. The process of rinsing with 100mL of distilled water before the MF procedure followed by 3, 30mL rinses after the sample was filtered was sufficient to ensure that no cross contamination occurred during the tests, which was confirmed by control samples that showed neither total coliform nor *E. coli* CFU.

The second technique used to assure validity of the field tests in the absence of methanol, was to thoroughly clean the filter funnel with 70% isopropyl alcohol after each day of testing. In other words, after six dilutions were run on one filter followed by a blank control and the source water microbial contamination tests were completed, the filter funnel was cleaned with alcohol. In the case of a day when post-alum and SolAgua water samples were being tested, the SolAgua water was run first, followed by post-alum water and then a blank control. After this series of tests, the filter funnel was again cleaned with alcohol.

2.4 Statistical Methods

To analyze the field and laboratory experiments, the most appropriate statistical test was unpaired/paired t-tests to compare baseline contamination and removal efficacy differences. To assess the validity of these tests both the assumptions for normality and equal variances were computed using the kurtosis and skewness variables for normality and an F-test for equal variances. If kurtosis and skewness values were greater than one or less than negative one, then the underlying distribution was not considered normal and failed the normality test.

Paired t-tests were used to compare baseline contamination of total coliforms with post-SolAgua water, since the underlying distribution did not violate the normality and equal variance assumptions. To analyze the remaining data, a Wilcoxon signed-rank test was performed as a nonparametric

analog to the paired t-test that tests the hypothesis that there is no difference between the median scores.

To analyze the removal efficacies of different samples, if the assumptions of normality and equal variances were not violated by the variable, then a two-sided unpaired t-test for sample means with equal variances at the .05 significance level was performed. Of the data collected for this study, the only variable that did not violate these assumptions was total coliforms for low versus high intensity UV-A radiation.

To compare the differences in removal efficacies of the remaining variables, a nonparametric equivalent to the two-sided unpaired t-test for sample means was used. The Wilcoxon Rank-Sum test is a nonparametric analog to the t-test for two independent samples and tests the hypothesis that the medians of two different samples are equal. This test is based on the ranks of the observed indicator organism removal efficacies.

Given that the source water was the same for both bags and that they were placed under the UV lamp at the same time, the two bag tests in the laboratory were not considered independent samples. There may be some relationship between how the bags were placed underneath the lamp that affects SolAgua disinfection of both bags. For example, depending on how the bags were lined up underneath the lamp, one bag may be exposed to more UV-A radiation than the second bag or vice-versa which would affect the microbial reduction of both bags. This indicates that the microbial reduction within both bags varies together depending on placement underneath the lamp. Although differences between bag placements between tests were minimized using bench markings, these samples will be weighted using sample weights to give a total sample size of ten to account for the lack of independence. If one of the two tests returned a value that was TNTC, then the value for the other bag was used to represent the newly weighted value.

2.5 Field Study Results

The source waters in Tamale and the surrounding communities ranged in their level of microbial contamination. The total coliform concentration averaged 13,194 CFU per 100mL and ranged from 500 CFU/100mL to 53,830 CFU/100mL. Concentrations of *E. coli* in the various water sources ranged from 50 CFU/100mL to 1,650 CFU/100mL and averaged 536 CFU/100mL.

Comparing the reduction in total coliforms at baseline and after SolAgua yielded a significant difference between the concentration of total coliforms tested at baseline and after SolAgua disinfection ($p=.004$), meaning that SolAgua water contains significantly less total coliforms than source water samples taken from the Northern Region. The reduction in total coliforms from the original source water was high (>99%) for both post-alum and SolAgua water (Table 1). Post-alum water removed, on average, 99.7% of total coliforms and SolAgua removed 100% on average. Given that the sensitivity of the MF method is 1 CFU/100mL and that only two samples were drawn from the post-SolAgua water, it is unlikely that SolAgua completely removed all total coliforms from the samples. The sensitivity of the MF method was not high enough to detect a smaller concentration of total coliforms.

The distribution of the underlying distribution violated the assumption of normality and equal variances; therefore, the Wilcoxon Rank-Sum test was performed. This test yielded no significant difference at the .05 level between the post-alum and the post-SolAgua samples for total coliforms

(p=.06). In the small study conducted in the field, the same removal efficacies were achieved using alum alone and alum combined with SolAgua disinfection; however the sample size was too small to detect a difference.

Table 1: Total Coliform Reduction in Eleven Different Source Waters of the Northern Region

Sample	Baseline [per 100mL]	Post- Alum [per 100mL]	Post-Alum & SolAgua [per 100mL]	Removal Efficacy Post-Alum	Removal Efficacy SolAgua
Ghanasco Muali Dam	6,733	6	0	99.9%	100.0%
Kaleriga Dam	14,300	30	0	99.8%	100.0%
Bipelar Dam	21,667	15	1	99.9%	100.0%
St. Mary's Dam*	53,830	14	2	100.0%	100.0%
Dungu Dam*	4,620	108	6	97.7%	99.9%
Libga Dam 1*	500	3	0	99.4%	100.0%
Bunglung Dam	5,150	1	0	100.0%	100.0%
Diare Dam	3,417	3	0	99.9%	100.0%
Libga Dam 2	1,417	0	0	100.0%	100.0%
Gbanyami Dam	19,333	0	0	100.0%	100.0%
Vitting Dam	14,167	0	0	100.0%	100.0%
			Average Removal Efficacy	**99.7%**	**100.0%**

*Cloudy/Overcast Day

In addition to total coliform removal, there was also a significant difference between *E. coli* concentrations at baseline and after alum administration and SolAgua disinfection (p=.009). *E. coli* reduction post-alum and within SolAgua was high (>99%) in nine samples tested in the Northern Region of Ghana (Table 2). On average, the removal efficacy of *E. coli* from baseline after post-alum samples was 99.4% and 100% for SolAgua samples. The Wilcoxon Rank-Sum test was performed using this data and there was no significant difference in the removal efficacy of *E. coli* using alum alone or alum combined with SolAgua disinfection (p=.153), likely due to the small sample size.

Table 2: *E. coli* Reduction in Nine Different Source Waters of the Northern Region

Sample	Baseline [per 100mL]	Post- Alum [per 100mL]	Post-Alum & SolAgua [per 100mL]	Removal Efficacy Post-Alum	Removal Efficacy SolAgua
Ghanasco Muali Dam	169	0	0	100.0%	100.0%
Kaleriga Dam	754	4	0	99.5%	100.0%
Bipelar Dam	100	4.5	0	95.5%	100.0%
St. Mary's Dam*	1,650	6	0	99.6%	100.0%
Dungu Dam*	133	0	0	100.0%	100.0%
Bunglung Dam	200	0	0	100.0%	100.0%
Libga Dam	50	0	0	100.0%	100.0%
Gbanyami Dam	367	0	0	100.0%	100.0%
Vitting Dam	1,400	0	0	100.0%	100.0%
			Average Removal Efficacy	**99.4%**	**100.0%**

*Cloudy/Overcast Day

This field data suggests that alum may be an adequate household water treatment technology in the Northern Region of Ghana, consequently, this treatment method warrants further exploration. This information also shows that SolAgua is able to remove any remaining coliforms and *E. coli* in the source water, resulting in drinking water where both indicator organisms are undetectable with the MF method. Overall, SolAgua disinfection combined with alum has significantly less total coliforms and *E. coli* than the original source water and has a high removal efficacy.

3. SolAgua Laboratory Study

3.1 Laboratory Study Design & Methods

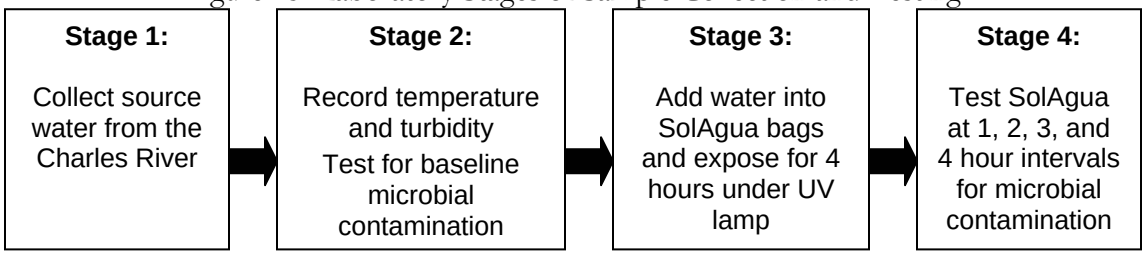
The laboratory portion of this study was conducted in March and April of 2007. This section will focus on the differences between the field and laboratory studies and outline the experimental design for the laboratory study. For example, the MF technique was used in both the field and laboratory investigations; therefore, it will not be described again in this section.

Figure 14: Laboratory Equipment

Source: Foran (2007)

Figure 14 shows the laboratory equipment used, including a pipette, tweezers, Petri dish, filter paper, filter and vacuum pump, methanol, alcohol, screwdriver, lighter, and a graduated cylinder. Metal Petri dishes were boiled for 10 minutes in water to sterilize them prior to use. An overview of the procedures conducted in the lab is illustrated in Figure 15.

Figure 15: Laboratory Stages of Sample Collection and Testing



3.1.1 Source Water

The purpose of this part of the study was to explore SolAgua time to disinfection time as it is affected solar radiation on sunny versus cloudy days if the source water did not have high turbidity and need alum coagulation as a prior step. The Charles River in Cambridge, Massachusetts provided a source of water that did not require pretreatment. Water was retrieved from the Charles River at the Harvard Bridge intersection of Massachusetts Avenue and Memorial Drive in quantities of five to ten liters in a five gallon plastic bucket. The laboratory was located 25 meters from the river;

therefore, the source water typically arrived at the laboratory for testing five minutes after collection and all baseline microbial testing was completed within one hour water collection.

3.1.2 Turbidity and Temperature

Turbidity was recorded using the HACH 2100P Portable Turbidimeter which has a range of 0 to 1,000 NTU. Immediately upon arrival at the laboratory, a small vial of source water was inserted into the instrument, the lid was closed, and the reading was recorded (Figure 16).

Figure 16: HACH 2100P Portable Turbidimeter

Source: Foran (2007)

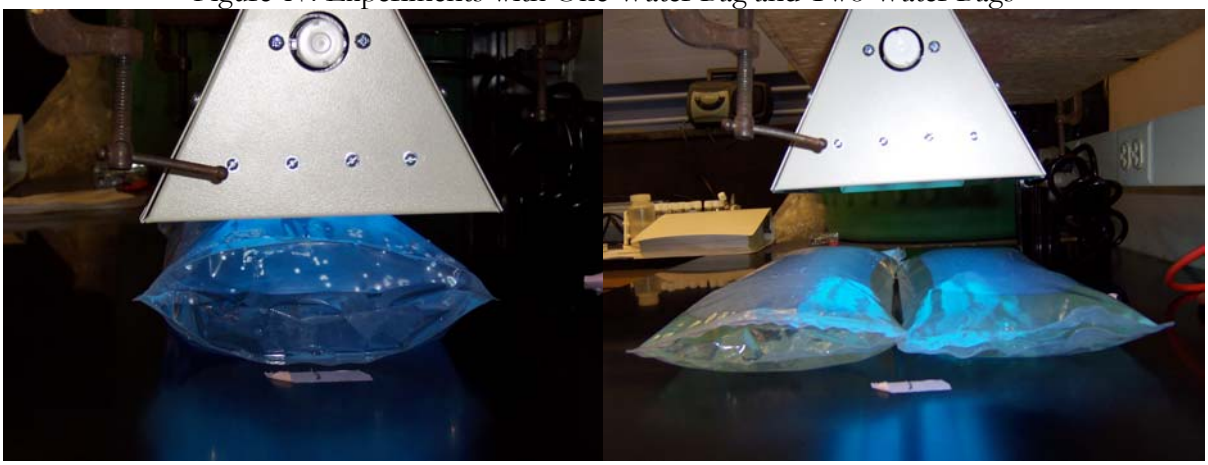
Turbidity measured within the appropriate range of less than 30 NTU and averaged 3.87 NTU across all 20 samples. Temperature was recorded at the same time as turbidity using a Celsius thermometer and was considerably less than the temperature one would normally find in the Northern Region of Ghana, ranging from 7°C to 10.5°C and averaging 9°C, it being winter when these tests were performed.

3.1.3 SolAgua Disinfection

To mimic appropriate solar conditions in the laboratory, a UVP XX-15L 365 nm wavelength UV bench lamp was fixed to a movable shelf in the laboratory (Figure 17). Since the primary mechanism of pathogen inactivation is UV-A radiation, this was the most appropriate way to imitate solar radiation (EAWAG/SANDEC, 2002).

Two comparison experiments were conducted in the laboratory. The first experiment used two bags simultaneously with the shelf elevated farther away from the bags to mimic a day in which solar radiation was not strong due to cloud cover. This was called "low intensity" UV-A radiation. In the second experiment, the lamp was lowered and one bag was placed underneath the lamp to create stronger solar radiation conditions representative of a sunny day, called "high intensity" UV-A radiation.

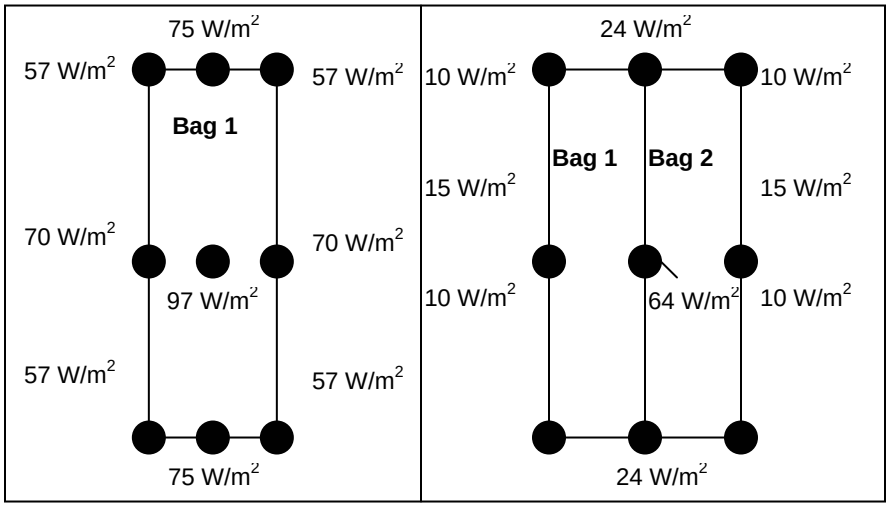
Figure 17: Experiments with One Water Bag and Two Water Bags



Source: Foran (2007)

To assess the validity of this experimental methodology, a pyranometer was used to measure solar irradiance of the lamp under the two different experimental conditions. The pyranometer is a small, glass dome with a metal body that has a sensor measuring a field of view of 180°. Figure 18 shows the difference in irradiance at the bench level between the experiments with one bag and those with two bags.

Figure 18: Irradiance Measurements with One and Two Bag Tests Using the Pyranometer



Irradiance was more direct for the one bag tests, which is what one would expect under direct solar radiation, so these tests will be called "sunny" solar condition tests and referred to as high intensity UV-A radiation. The two bag tests were not always receiving direct radiation from the UV lamp since part of the bags overlapped outside of the lamp. In addition, the intent was to create a greater distance between the bags and the lamp; therefore, these bags are receiving less radiation and will be considered "cloudy" solar condition experiments and referred to as low intensity UV-A radiation. The pyranometer was used to measure irradiance at points around each bag in both experiments (Figure 18).

The pyranometer values were then compared with existing estimates of the dosage of UV-A necessary to kill *E. coli* and disinfect the water. Wegelin, et al. showed that the fluence necessary for a 3-log reduction of *E. coli* was approximately 2,000 kJ/m^2 or 555 $W \bullet h/m^2$, "…dose of solar radiation integrated in the 365-400 nm wavelength range," and corresponded to approximately 5 hours of mid-latitude midday sunshine during the summer months (Wegelin, 1994). If one assumes a linear relationship between mid-latitude sunshine and the fluence required for a 3-log reduction of *E. coli*, then the dosage of fluence necessary during one hour of exposure to UV-A radiation is approximately 111 W/m^2. By performing the experiments in the laboratory, the assumption is that intensity in and of itself does not have an effect on disinfection or that 1 hour at 555 W/ m^2 is equivalent to 5 hours at 111 W/m^2 or, for that matter, 555 hours at 1 W/ m^2. This is unlikely to be true.

The single bag experiments are close to reaching the desired dose of irradiation of 111 W/m^2 in the center of the bag, although the radiation is not as strong at the corners of the bag. Consequently, 1 hour of exposure under the UV lamp in the lab may translate into less than an hour of solar radiation for both the "sunny" and "cloudy" tests. This allows for a conservative estimate of time whereby, if the removal efficacy is considered adequate after four hours in the lab, the recommendation for four hours of exposure under typical solar conditions will be more than adequate to achieve the same or improved removal efficacy.

The laboratory conditions are limited in their ability to interpolate the exact solar conditions in the field that translate into the "cloudy" conditions created in the laboratory. The low UV-A radiation condition created approximates solar radiation that is less than the dose of radiation that corresponds to 5 hours of mid-latitude midday sunshine during the summer months as described by Wegelin and colleagues. By calling this condition "cloudy", the assumption is that less radiation at the bag level corresponds to natural sunlight that is less strong because of cloudy or overcast conditions.

The bags were placed underneath the lamps and tested for total coliforms and *E. coli* after 1, 2, 3, and 4 hours respectively. In this manner, one is able to analyze the reduction of the microbiological indicator organisms over time to potentially provide recommendations for implementation under two different radiation conditions. A total sample size of 10 bags for the one bag test and 20 bags (2 bags on 10 separate occasions) was analyzed.

3.2 Laboratory Results

Source water microbial contamination of total coliforms in the Charles River averaged 4,973 CFU/100mL and ranged between 1,193 CFU/100mL and 12,100 CFU/100mL. *E. coli* contamination in the Charles River averaged 411 CFU/100mL, ranging from 53 CFU/100mL and 2,260 CFU/100mL. The microbial contamination of the Charles River water fluctuated depending on precipitation events. On average, the microbial contamination found in the Charles River was less than that found in the water sources of the Northern Region.

Table 3: Source Water Microbial Contamination of Northern Region and Charles River

	Northern Region [TC* /100mL]	Charles River [TC* /100mL]	Northern Region [EC† /100mL]	Charles River [EC† /100mL]
Sample Size (n)	11	20	9	20
Minimum	500	1,130	50	53
Maximum	53,830	12,050	1,650	2,260
Average	**13,194**	**4,597**	**536**	**411**

*TC = Total Coliforms
†EC = *E. coli*

Nevertheless, when the two distributions of *E. coli* source water contamination were compared using the Wilcoxon Rank-Sum test, there was no significant difference between the two groups (p=.0818) at the .05 significance level. It may be that the sample size is not large enough to detect this difference; however, for the purposes of this study this leads to a level of comparability between source waters and allows greater generalizability of removal efficacies of *E. coli* by SolAgua in both the field and laboratory studies. Since *E. coli* is a better indicator of fecal contamination than total coliforms, this comparability is advantageous for drawing preliminary conclusions about SolAgua's performance under various environmental conditions, recognizing that the small sample size remains a barrier to drawing conclusive results.

3.2.1 SolAgua's Performance under Low and High UV-A Radiation

An analysis of the source water contamination with the nonparametric equivalent of a paired t-test showed there was a significant difference between total coliforms at baseline and SolAgua under both high and low UV-A radiation exposure for four hours (p=.006). The difference between *E. coli* concentrations at baseline and SolAgua after four hours under both low and high UV-A radiation was also statistically significant (p=.006).

3.2.2 Low Intensity vs. High Intensity UV-A Radiation (4 hour comparison)

Since the assumptions of normality and equal variances were not violated by the total coliform distribution, an unpaired t-test of equal variances was performed. There is a significant difference between removal efficacies of total coliforms in low versus high intensity UV-A radiation (p=.001) after four hours of exposure. The "sunny" conditions created in the laboratory are more efficient at removing total coliforms than the "cloudy" conditions created in the laboratory.

The distribution of *E. coli* variables violated the normality assumption. The Wilcoxon Rank-Sum test yields a significant difference in removal efficacies under low and high intensity UV-A radiation (p=.042) after four hours. The high intensity UV-A radiation achieves more efficient transfer of radiation to the source water than the low intensity UV-A radiation tests, thereby realizing a better removal efficacy of *E. coli*. Overall, higher intensity UV-A radiation resulted in a significantly better reduction of the indicator organisms of interest when compared to the low intensity UV-A radiation based on the "sunny" versus "cloudy" solar radiation conditions created in the laboratory.

Table 4: Removal Efficacy of Total Coliforms and *E. coli* Under Low and High UV-A Radiation after 4 Hours of Exposure

	Total Coliform Removal Efficacy	***E. coli* Removal Efficacy**
High Intensity 4 Hours	99.2%	100.0%
Low Intensity 4 Hours	95.6%	99.0%

Low UV-A radiation achieved a moderate (90-99%) reduction of total coliforms and *E.* coli while high UV-A radiation achieved a high reduction of total coliforms and *E. coli.*

3.2.3 Low Intensity (4 hour) vs. High Intensity UV-A Radiation (1, 2, 3 hours)

Valid colony counts were not achieved at low intensity UV-A radiation in a substantial portion of the samples at one, two, and three hours because proper dilutions were not made in the laboratory to achieve a large enough sample size. No comparisons can be made to show the reduction over time of total coliforms or *E. coli* between low intensity samples.

A meaningful comparison can be made showing differences in low intensity UV-A radiation at four hours versus high intensity UV-A radiation at one, two, and three hour intervals. Since, the colony counts of low intensity UV-A radiation at one, two, and three hours were often TNTC, one can make a logical assumption, that these removal efficacies were less than those at 4 hours. For total coliform analysis the underlying distribution was normal, therefore unpaired two-sided t-tests were performed, and the Wilcoxon Rank-Sum test was used for analyzing *E. coli* samples given that the underlying distribution was not normally distributed.

The removal efficacy of total coliforms and *E. coli* under high intensity UV-A radiation after 1, 2 and 3 hours as compared to the low intensity UV-A radiation after four hours, are show in Tables 5 and 6. The total coliform samples diverge after three hours of exposure under the two different radiation conditions as the higher intensity UV-A radiation achieves more efficient reduction in total coliforms somewhere between two and three hours of exposure.

Table 5: Comparison of Total Coliform Removal for Cloudy and Sunny Laboratory Conditions

Comparison Groups	**n**	**Average Removal Efficacy**	**p-value**
High Intensity 1 Hour vs. Low Intensity 4 Hours			
High Intensity 1 Hour	10	85.7%	0.14
Low Intensity 4 Hours	10	95.6%	
High Intensity 2 Hours vs. Low Intensity 4 Hours			
High Intensity 2 Hours	10	95.7%	0.47
Low Intensity 4 Hours	10	95.6%	
High Intensity 3 Hours vs. Low Intensity 4 Hours			
High Intensity 3 Hours	10	98.7%	0.001
Low Intensity 4 Hours	10	95.6%	
High Intensity 4 Hours vs. Low Intensity 4 Hours			
High Intensity 4 Hours	10	99.2%	0.001
Low Intensity 4 Hours	10	95.6%	

Removal efficacies of *E. coli* show a slightly different pattern after comparing the differences between low intensity UV-A radiation after four hours and high intensity UV-A radiation at one-hour intervals (Table 6). There is only a significant difference between the high and low intensity UV-A radiation samples after both have been exposed for four hours. This is likely due to the small sample size of the laboratory study, that we do not see a significant difference at an earlier hour.

Table 6: Comparison of *E. coli* Removal for Cloudy and Sunny Laboratory Conditions

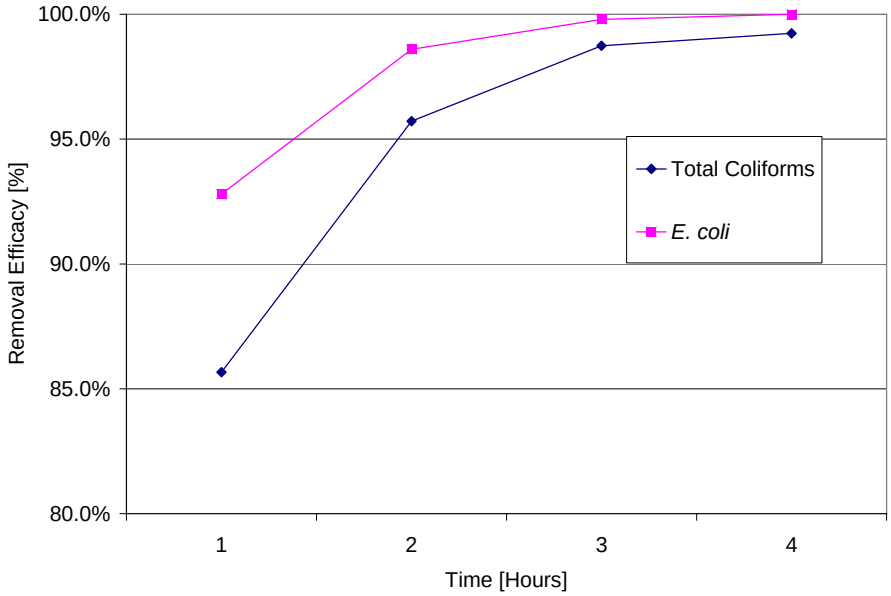
Comparison Groups	n	Average Removal Efficacy	p-value
High Intensity 1 Hour vs. Low Intensity 4 Hours			
High Intensity 1 Hour	10	92.8%	<.001
Low Intensity 4 Hours	10	99.0%	
High Intensity 2 Hours vs. Low Intensity 4 Hours			
High Intensity 2 Hours	10	98.6%	0.43
Low Intensity 4 Hours	10	99.0%	
High Intensity 3 Hours vs. Low Intensity 4 Hours			
High Intensity 3 Hours	10	99.8%	0.12
Low Intensity 4 Hours	10	99.0%	
High Intensity 4 Hours vs. Low Intensity 4 Hours			
High Intensity 4 Hours	10	100.0%	0.04
Low Intensity 4 Hours	10	99.0%	

Given the small sample size, it is important to analyze the overall removal efficacy of each of the solar conditions created in the laboratory over the four hour period. SolAgua disinfection achieves a high reduction of *E. coli* after three hours of exposure to high intensity UV-A radiation, but is not able to achieve a high reduction of total coliforms under the low intensity UV-A radiation after four hours or high intensity UV-A radiation after three hours.

3.2.4 Removal Efficacy of High Intensity UV-A Radiation

Ideal conditions for SODIS in PET plastic bottles and SolAgua are present where solar radiation is the strongest. For that reason, it is valuable to investigate the removal efficacy of high intensity UV-A radiation over the complete four hour period of exposure in the laboratory. The data collected from the high intensity UV-A radiation tests show a low reduction (<90%) of total coliforms and a moderate reduction of *E. coli* after only one hour of exposure (Figure 19), 85.7% and 91.2% respectively. This was also the period of time when the temperature of the samples increased the most, rising from an average of 7.9°C at baseline to 20.3°C at the end of the first hour. This study does not aim to disentangle the relative contribution of UV-A radiation and temperature, but it is valuable to note that the removal efficacies were low to moderate in the first hour with a low baseline source water temperature. Past studies have found that the thermal effects of the rising water temperature are synergistic only at temperatures between 50°C and 60°C (EAWAG/SANDEC, 2002; McGuigan, Joyce, Conroy, Gillespie, & Elmore-Meegan, 1998; Wegelin, 1994), which were not achieved during the four hours of laboratory exposure. After four hours of exposure, the average temperature of the source water under the high intensity UV-A radiation was 29.9°C.

Figure 19: Removal Efficacies of Total Coliforms and *E. coli* under High Intensity UV-A Radiation



After two hours of exposure to the high UV-A radiation, 95.7% of total coliforms and 98.6% of *E. coli* were removed, which shows that two hours may be an adequate exposure time to achieve a moderate reduction of microbial contamination for SolAgua under sunny weather conditions. Four hours of exposure to high UV-A radiation yields a removal of 99.2% of total coliforms and 100.0% of *E. coli*, which is a more appropriate recommendation even under "sunny" conditions created in the laboratory. SODIS studies have found that exposure to UV radiation and heating to temperatures between 50°C and 60°C are high enough to cause a reduction of at least 99.9% of bacteria over a period of one to several hours (Rijal, 2001). The results found in this study confirm that a reduction of at least 99.9% of *E. coli* was possible, but this reduction did not occur for total coliforms. Considering that the laboratory tests did not achieve temperatures of 50-60°C, SolAgua performed well with high microbial reduction of total coliforms and *E. coli*. These laboratory tests add to the body of evidence suggesting that high temperatures do not need to be achieved for solar disinfection to occur and that UV-A radiation is a mechanism by which pathogens are inactivated.

4. Discussion

4.1 SolAgua Potentials

The average removal efficacies of both total coliforms and *E. coli* after alum administration and SolAgua were high and showed no significant difference. The alum removed 99.7% of total coliforms and 99.4% of *E. coli*, which is a substantial amount of baseline contamination removed. This was an unexpected and interesting finding, identifying the possibility that in highly turbid source waters in the region, alum alone may achieve enough of a reduction in fecal contamination to have a significant health impact. Women in the region are known to use alum as a household water treatment method and although this study used one alum ball per sample tested (10 liters of water), the alum ball can be used multiple times. It would be interesting to further explore how alum could be used as a household water treatment method in the Northern Region to determine if this method is successful in achieving improved health. This study did not aim to explore alum as an HWTS method; however, this finding deserves further study.

That said, SolAgua was able to remove the remaining total coliforms and *E. coli* to achieve a high reduction of both indicator organisms after alum was administered. This evidence is a first step in showing that SolAgua is able to perform solar disinfection over a reasonable period, four hours, of sun exposure. These field studies identified a need to explore the role of solar radiation, specifically, the limitations of strength of solar radiation on sunny versus cloudy days. This information will help guide recommendations to users on the duration of bag exposure necessary to remove pathogens. The current recommendation of 2-4 hours should be explored further to determine the most conservative recommendation to users to assure that they are not at risk of drinking unclean water. Four hours may not be enough time on cloudy days and two hours of exposure on sunny days may only achieve a moderate reduction of pathogenic agents. The data collected in the field included three days (St. Mary's Dam, Dungu Dam and Libga Dam 1) which were considered cloudy and overcast, however, SolAgua still efficiently removed the total coliforms and *E. coli* when used for a full four hours on those samples. This extremely small sample size, however, does not provide enough evidence to soundly confirm that four hours of sun exposure on cloudy days is adequate.

The laboratory study helped explore the possibility that cloudy conditions may require a longer exposure time. Exposure to UV-A radiation is a significant factor in the reduction of total coliforms and *E. coli* over time and exposure for four hours at a time does significantly reduce the concentration of both indicator organisms under both the low and high intensity UV-A radiation conditions. Although four hours appears to be enough under the cloudy conditions created in the laboratory, exposure to UV-A radiation alone in the laboratory is not a direct substitute for exposure to direct solar radiation and natural weather conditions. The intensity of UV-A radiation of the cloudy conditions created in the laboratory may not be analogous to naturally occurring field conditions. To conclusively flush out the recommendation of four hours of exposure under all solar conditions, both cloudy and sunny, there needs to be much more substantial studies with larger sample sizes in the field. Four hours of exposure to sunlight is a conservative estimate for sunny days and disinfection is likely occurring earlier at the minimum recommended time of two hours. To be conservative, four hours should remain the recommendation for the time being, until more extensive research can be completed.

The meteorological conditions such as intensity of solar radiation in Ghana support the feasible implementation of SolAgua disinfection; unfortunately, there remain a series of other challenges that are considerable barriers to SolAgua implementation.

4.2 Challenges to SolAgua Implementation

This thesis has illustrated several challenges to the implementation of SolAgua and, more broadly, solar disinfection technologies in the Northern Region of Ghana.

4.2.1 Guinea Worm

First, the presence of guinea worm and the absence of knowledge supporting SolAgua's ability to remove the guinea worm copepod pose a significant barrier to implementation. No technology in this region of the world can be implemented without confirmation that users will not be at risk of contracting guinea worm. Or if it is determined that users may be at risk, then there is a need to recommend the use of a guinea worm cloth filter in conjunction with that technology.

4.2.2 High Turbidity – Multiple Behavior Changes

The high turbidity of source water during the rainy season adds an additional step in the household water treatment process that will likely be a behavior change challenge. The field study demonstrated one method of using SolAgua in the Northern Region. This procedure followed three steps: pre-treatment of the water using alum, passage of the water through a cloth filter to assure copepod removal, and finally exposure of the water to solar radiation for at least four hours in SolAgua.

A study with a factorial design would be needed to examine whether it is necessary for an individual to follow this series of steps to achieve safe drinking water with SolAgua in the region. If a study concluded these three steps were necessary, then there are behavior change considerations that would pose significant challenges to SolAgua implementation in the region. SODIS in PET plastic bottles, in particular, has been shown to have poor uptake and acceptability ratings in the field (Rainey & Harding, 2005). A study in Nepal recorded only a 9% adoption rate of SODIS in the study population and identified that a poor understanding of the link between drinking untreated water and disease was one barrier to SODIS uptake (Rainey & Harding, 2005).

In general, behavior change promotions that are narrowly focused are more likely to be successful (Hernandez, 2007). A campaign that promoted SolAgua in the region would benefit from focusing on a series of three major behavior changes using: alum, cloth filter, and SolAgua. Given that SODIS itself faces acceptability challenges in the field, it seems unlikely that people will perform a series of two additional steps prior to using a solar disinfection product- be it SODIS bottles or bags.

4.2.3 Family Size

Another challenge to SolAgua implementation is the large family size in the region. Although the country-wide family size average is 4.3 members per household in the rural areas and 3.6 members per household in the urban areas (DHS, 2003), polygynous unions are common in the villages of the Northern Region and family sizes can be quite large. 28.8% of married men in the Northern Region have more than one wife and 43.9% of currently married women have at least one other co-wife (DHS, 2003). Johnson, in her survey of households in the Northern Region found the average family size to be 12 in a small, cross-sectional sample of 41 households (Johnson, 2007). While this

finding is not generalizable to the region, it does sample the communities where PHW is actively promoting and disseminating HWTS technologies. If each individual consumes an average of two liters of water per day (a conservative estimate which is likely to be higher during the dry season), then each individual would require one, 2 liter bag to provide their drinking water needs for that day. SolAgua is perceived as a low-cost alternative to the ceramic filter that PHW is promoting, however, if each person needs one bag and the bags have a short life-span then this may not be the most low-cost or appropriate solution for individuals in the region. PHW is currently selling the ceramic filter for as low as $6 in the rural communities and as much as $12 in Tamale proper and other more economically advantaged areas.

SolAgua can theoretically be locally manufactured at a low-cost; nevertheless, if the bag is not made from a durable plastic it will easily fail under repeated use. This results in an environmental impact of plastic waste in an area where there are no formal garbage disposal facilities and household garbage is either littered around the community or burned giving off toxins which are harmful to people and the environment. SolAgua needs to be manufactured from a thicker plastic with a high quality heat sealer if levels of durability and robustness are to be accurately tested in the field. This will require a tradeoff between a more robust product and a slower time to disinfection from decreased solar radiation penetration and, therefore, less efficient removal of pathogens. The environmental impact of SolAgua will always be a concern and a local solution should be employed, such as a possible exchange program where used bags are returned for a discount on new bags. This way the old bags can be properly disposed of and reduce the negative environmental impact.

Considering both the large family size and the durability issues, SolAgua may not be the most low-cost solution for poor families in this region. Although the bag manufacturing price is unknown, it is estimated that one bag could be manufactured for approximately $0.15 per bag. Given that the lifespan of the bag is unknown because of remaining questions of durability and the large family size in the region, the up-front cost would be $3.00 for a family of 20. In the experience of this researcher, SolAgua bags did not last the cycle of testing before they leaked and failed to be of adequate use. This type of durability would put undue financial pressure on poor families in the region. This cost also does not include the price of alum balls in the market which was $0.02-0.03 per ball during the July of 2006, which most families may need to purchase in order to pre-treat the water before using SolAgua. The cost is too much for families in the region, especially when 44.8% of the population of Ghana lives on less than a dollar a day (UNDP, 2000) and 69% of the population in the Northern Region lives below the poverty line (IPC/UNDP, 2004).

4.2.4 Harmattan

Harmattan occurs between November and March in Ghana and is characterized by a dry, dusty wind that blows southwest across the Sahara and into the Gulf of Guinea. These winds carry fine dust and particulates which severely limit visibility ("harmattan", 2007) and can both scatter and absorb solar radiation (Sokolik & Toon, 1996). During January 2007, Yazdani conducted research on a solar disinfection technology, SOLAIR, in the Northern Region and found that UV radiation was 80% less than the peak potential expected on a clear, cloudless day at this latitude and time of year (Yazdani, 2007). This finding poses another potential challenge to SolAgua implementation in the Northern Region. Further investigation is needed to explore the impact of reduced UV radiation during harmattan on SolAgua's ability to disinfect water over the current recommended period of 2-4 hours of sun exposure.

4.3 Study Limitations

Both the laboratory and field studies have several limitations that need to be considered. There is a small sample size for both portions of the study that limit the ability of the study to be generalizable. The field study has a sample size of 11 and the laboratory study examined 20 samples. As a result, normally distributed "data" was not obtained, but nonparametric statistical methods were used to show significant results. One would expect that if the sample size had been larger then the "data" collected would have been normally distributed and parametric statistical methods could have been used to illustrate significant differences between the removal efficacy of SolAgua under various environmental and source water conditions.

Ideally, during the field portion of this study, SolAgua disinfection would have been performed on the same day as source water sample collection because there is the potential for natural die off or growth of pathogens if the water was left out of the supply source for an extended period of time (APHA, 1981). However, because source water collection typically required several hours, it was necessary to wait until the next day to expose the source water to SolAgua. While this may not be ideal for microbiological testing, this reflects water collection by people in the region. Women often fetch water in the late hours of the afternoon and would not be able to perform SolAgua disinfection until the day after water collection to take advantage of the strongest hours of solar radiation. Therefore, the process used more closely approximates actual conditions and more closely approximates effectiveness of SolAgua versus efficacy- effectiveness referring to how SolAgua disinfection would perform under typical conditions and efficacy referring to how SolAgua disinfection performs under controlled/ideal conditions.

The laboratory portion of the study is based on a major assumption that by exposure to UV-A radiation in a controlled environment and measuring irradiation of the UV lamp, one is able to mimic exposure to the sun within the appropriate latitude range. This assumption is based on evidence from previous solar disinfection experiments and is grounded in the understanding that UV-A radiation is one of the two primary mechanisms by which pathogens are inactivated by SODIS in PET plastic bottles and bags. In addition, Figure 5 shows the range of UV-A radiation that will inactivate fecal coliforms in both SODIS bags and bottles, and the UV-A doses achieved in the laboratory are within these ranges.

The source water used in the laboratory experiments is another potential study limitation. The average temperature of the source water was 9°C with a range of 7°C to 10.5°C. Source water temperature in areas where solar disinfection is most appropriate is unlikely to be this cold. It is possible that inactivation by UV-A radiation occurred at a slower rate during exposure because of the cold initial temperature. The study results, however, show that the removal efficacy over four hours was high and while the first hour may not reflect field conditions, substantial removal of both total coliforms and *E. coli* were obtained over the four hour period.

Despite the study limitations, "data" was collected using valid techniques and statistical methods were used to show meaningful differences and highlight the time to disinfection of SolAgua under both cloudy and sunny conditions. These two studies can serve as a preliminary tool to inform future research on SolAgua.

5. Recommendations

5.1 Pure Home Water

After a thorough discussion of the results and implications from the field and laboratory studies, it is this researcher's recommendation that neither SolAgua nor SODIS in PET bottles be pursued as a viable household water treatment technology in the Northern Region of Ghana. Source water turbidity conditions, reduced UV radiation during harmattan, behavior change challenges, and the presence of guinea worm pose too many barriers to the successful implementation of this particular technology. The current ceramic filter product provides a solution that is better proven microbiologically and in the presence of guinea worm, more robust, and acceptable to the target population. SolAgua was originally pursued as a potential low-cost alternative to the ceramic filter, but the ceramic filter may in reality be more affordable over the lifetime of the filter- 3 years.

5.2 SolAgua Team

SolAgua, within these two small studies, has been shown to remove a substantial amount of baseline contamination in low-turbid source water. The current recommendation of 2-4 hours of sun exposure should be modified slightly to be more conservative. Users should be encouraged to expose the bags for at least four hours and if the conditions are cloudy or there is reduced visibility then to expose it for at least 6-8 hours to be safe. Knowing that SolAgua is still in development, with no current plans for expansion at this time, further research should focus on the trade-offs between using thicker plastics versus microbiological quality improvement over time. With this information in hand, the D-Lab team and other interested parties will be able to expand the technology knowing that they are providing users with a product that is both durable and efficiently disinfects the source water.

Finally, field studies on user acceptability and behavior change limitations should be conducted in this preliminary development stage to improve design and knowledge of the potential user base. In addition, given the environmental impact concerns outlined here, the SolAgua team should seriously consider a lifecycle analysis of the product and collect user impressions. If plastic bottles are already available for collection in a particular location, perhaps it would be best to take advantage of this resource instead of creating more plastic garbage in areas where garbage disposal is severely limited.

5.3 Future Research

SODIS in PET bottles or SolAgua bags should be analyzed further to determine if the guinea worm copepod can be eliminated through exposure to solar radiation. This is one area of research that will illuminate a gap in the knowledge base. Finally, one positive byproduct of this research was identifying the ability of alum to be quite effective at improving overall water quality. While this is a common pre-treatment method in large-scale water treatment processes, perhaps there are circumstances under which promoting alum alone would achieve a significant reduction in diarrheal morbidity. This is worth exploring further, since this is a locally available resource that is acceptable to women in the region.

SolAgua should continue to be studied by the project team to determine the most appropriate areas of the world for successful implementation; however, the Northern Region of Ghana for the reasons outlined in this study, poses too many barriers for successful and sustained use of SolAgua and SODIS as a suitable household water treatment technology.

6. References

Acra, A., Raffoul, Z., & Karahagopian, Y. (1984). Solar Disinfection of Drinking Water and Oral Rehydration Solutions. *UNICEF, Paris*.

Alhassan, H., & Salifu, W. (2006). *Pure Home Water Social Business Plan*. Tamale, Ghana.

APHA. (1981). *Standard Methods for the Examination of Water and Wastewater* (21st ed.).

Cairncross, S., & Feachem, R. G. (1996). *Environmental Health Engineering in the Tropics* (Second ed.). Chichester.

CDC. (2004). Dracunculiasis Guinea Worm Disease. *Centers for Disease Control and Prevention, Atlanta*.

CDC. (2007a). *Guinea Worm Wrap-Up #169*. Atlanta: WHO Collaborating Center for Research, Training and Eradication of Dracunculiasis

CDC. (2007b). *Guinea Worm Wrap-Up #170*. Atlanta: WHO Collaborating Center for Research, Training and Eradication of Dracunculiasis

Chiller, T. M., Mendoza, C. E., Lopez, M. B., Alvarez, M., Hoekstra, R. M., Keswick, B. H., et al. (2006). Reducing diarrhoea in Guatemalan children: randomized controlled trial of flocculant-disinfectant for drinking-water. *Bull World Health Organ, 84*(1), 28-35.

Clasen, T., Roberts, I., Rabie, T., Schmidt, W., & Cairncross, S. (2006). Interventions to improve water quality for preventing diarrhoea. *Cochrane Database Syst Rev, 3*, CD004794.

Clasen, T. F., & Bastable, A. (2003). Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use. *J Water Health, 1*(3), 109-115.

Clasen, T. F., Brown, J., Collin, S., Suntura, O., & Cairncross, S. (2004). Reducing diarrhea through the use of household-based ceramic water filters: a randomized, controlled trial in rural Bolivia. *Am J Trop Med Hyg, 70*(6), 651-657.

Conroy, R. M., Elmore-Meegan, M., Joyce, T., McGuigan, K. G., & Barnes, J. (1996). Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial. *Lancet, 348*(9043), 1695-1697.

Conroy, R. M., Meegan, M. E., Joyce, T., McGuigan, K., & Barnes, J. (1999). Solar disinfection of water reduces diarrhoeal disease: an update. *Arch Dis Child, 81*(4), 337-338.

Conroy, R. M., Meegan, M. E., Joyce, T., McGuigan, K., & Barnes, J. (2001). Solar disinfection of drinking water protects against cholera in children under 6 years of age. *Arch Dis Child, 85*(4), 293-295.

Control of Communicable Diseases Manual. (18th ed.)(2004). 18th ed.). Washington, DC: American Public Health Association.

DHS. (2003). Ghana: DHS, 2003 - Final Report. *Demographic and Health Surveys, Maryland.*

EAWAG/SANDEC. (2002). *Solar Water Disinfection A Guide for the Application of SODIS*. Duebendorf, Switzerland: Swiss Federal Institute of Environmental Science and Technology (EAWAG), Department of Water and Sanitation in Developing Countries (SANDEC).

Feachem, R. G., D.J. Bradley, H. Garelick and D.D. Mara. (1983). *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management*. New York.

Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L., & Colford, J. M., Jr. (2005). Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *Lancet Infect Dis, 5*(1), 42-52.

The Global Burden of Disease. (1996).). Cambridge: Harvard University Press.

GSS. (2005). 2000 Population and Housing Census: Analysis of District Data and Implications for Planning - Norhtern Region. *Ghana Statistical Service, Accra.*

harmattan. (2007). Retrieved May 5, 2007, from Encyclopedia Britannica Online: http://www.search.eb.com/eb/article-9039291

Hernandez, O. (2007). *Measuring Behavioral Outcomes when Promoting Household Water Treatment and Storage Discussion Paper for E-conference Hosted by USAID/HIP*: Hygiene Improvement Project Academy for Educational Development.

IPC/UNDP. (2004). *Elements of an Employment Framework for Poverty Reduction in Ghana*. Amherst: International Poverty Centre and United Nations Development Programme.

Johnson, S. (2007). *Health and Water Quality Monitoring of Pure Home Water's Ceramic Filter Dissemination in the Northern Region of Ghana.* Massachusetts Institute of Technology, Cambridge, MA.

Lopez, A. D., Mathers, C. D., Ezzati, M., Jamison, D. T., & Murray, C. J. (2006). Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. *Lancet, 367*(9524), 1747-1757.

Mattelet, C. (2006). *Household Ceramic Water Filter Evaluation Using Three Simple Low-Cost Methods: Membrane Filtration, 3M Petrifilm and Hydrogen Sulfide Bacteria in Northern Region, Ghana.* Massachusetts Institute of Technology, Cambridge, MA.

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. *J Appl Microbiol, 84*(6), 1138-1148.

Millipore. *Water Microbiology Laboratory and Field Procedures*.

Murcott. (2006). *Status of Implementation, Critical Factors, and Challenges to Scale-Up of Household Drinking Water Treatment and Safe Storage Systems. Paper submitted for e-conference on household water treatment and safe storage. http://www.hip.watsan.net*.

Nath, K. J., Bloomfield, S., & Jones, M. (2006). *Household water storage, handling and point-of-use treatment. A review commissioned by IFH; published on http://www.ifh-homehygiene.org.* International Scientific Forum on Home Hygiene (IFH).

Pruss, A., Kay, D., Fewtrell, L., & Bartram, J. (2002). Estimating the burden of disease from water, sanitation, and hygiene at a global level. *Environ Health Perspect, 110*(5), 537-542.

Quick, R. E., Kimura, A., Thevos, A., Tembo, M., Shamputa, I., Hutwagner, L., et al. (2002). Diarrhea prevention through household-level water disinfection and safe storage in Zambia. *Am J Trop Med Hyg, 66*(5), 584-589.

Quick, R. E., Venczel, L. V., Mintz, E. D., Soleto, L., Aparicio, J., Gironaz, M., et al. (1999). Diarrhoea prevention in Bolivia through point-of-use water treatment and safe storage: a promising new strategy. *Epidemiol Infect, 122*(1), 83-90.

Rainey, R. C., & Harding, A. K. (2005). Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *Int J Environ Health Res, 15*(5), 361-372.

Rijal, G., Fujioka, RS. (2001). Synergistic effects of solar radiation and solar heating to disinfect drinking water sources. *Water Sci Technol, 43*(12), 155-162.

Sobsey, M. (2002). Managing Water in the Home: Accelerated Health Gains from Improved Water Supply. *World Health Organization, Geneva.*

Sokolik, I. N., & Toon, O. B. (1996). Direct radiative forcing by anthropogenic airborne mineral aerosols. *Nature, 381*(6584), 681-683.

Thompson, T., & Khan, S. (2003). Situation analysis and epidemiology of infectious disease transmission: a South-East Asian regional perspective. *Int J Environ Health Res, 13 Suppl 1*, S29-36.

UNDP. (2000). Human Development Report 2000. *United Nations Development Programme*.

UNICEF. (2005). At a glance: Ghana [Accessed at: http://www.unicef.org/infobycountry/ghana.html].

VanCalcar, J. (2006). *Collection and Representation of GIS Data to Aid Household Water Treatment and Safe Storage Technology Implementation in the Northern Region of Ghana*. Massachusetts Institute of Technology, Cambridge, MA.

Viessman, W., Hammer, M. (1998). *Water Supply and Pollution Control* (Sixth ed.). Menlo Park: Addison Wesley Longman, Inc.

Wegelin, M., S. Canonica, K. Mechsner, T. Fleischmann, F. Pesaro, and A. Metzler. (1994). Solar water disinfection: scope of the process and analysis of radiation experiments. *J Water SRT-Aqua, 43*(3), 154-169.

WHO. (2006). Guidelines for Drinking-water Quality First Addendum to Third Edition. *World Health Organization, Geneva*.

WHO. (2007a). Environmental Health in Emergencies and Disasters: Fact Sheet 2.33. from http://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_33.pdf

WHO. (2007b). The International Network to Promote Household Water Treatment and Safe Storage., from http://www.who.int/household_water/en/

WHO/UNICEF. (2004). *Meeting the MDG Drinking Water and Sanitation Target: A Mid-Term Assessment of Progress*. New York: World Health Organization and United Nations Children's Fund.

WHO/UNICEF. (2006). *Meeting the MDG Drinking Water and Sanitation Target the Urban and Rural Challenge of the Decade*. New York: World Health Organization and United Nation's Childrens Fund.

Yazdani, I. (2007). *High Density Polyethylene (hdpe) Containers as an alternative to Polyethylene terephthalate (PET) bottles for solar disinfection of drinking water in Northern Region, Ghana*. Massachusetts Institute of Technology, Cambridge, MA.

7. Appendices

Appendix A - Performance & Health-based Targets for Water Quality

Figure 7.2 Performance targets for selected bacterial, viral and protozoan pathogens in relation to raw water quality (to achieve 10^{-6} DALYs per person per year)

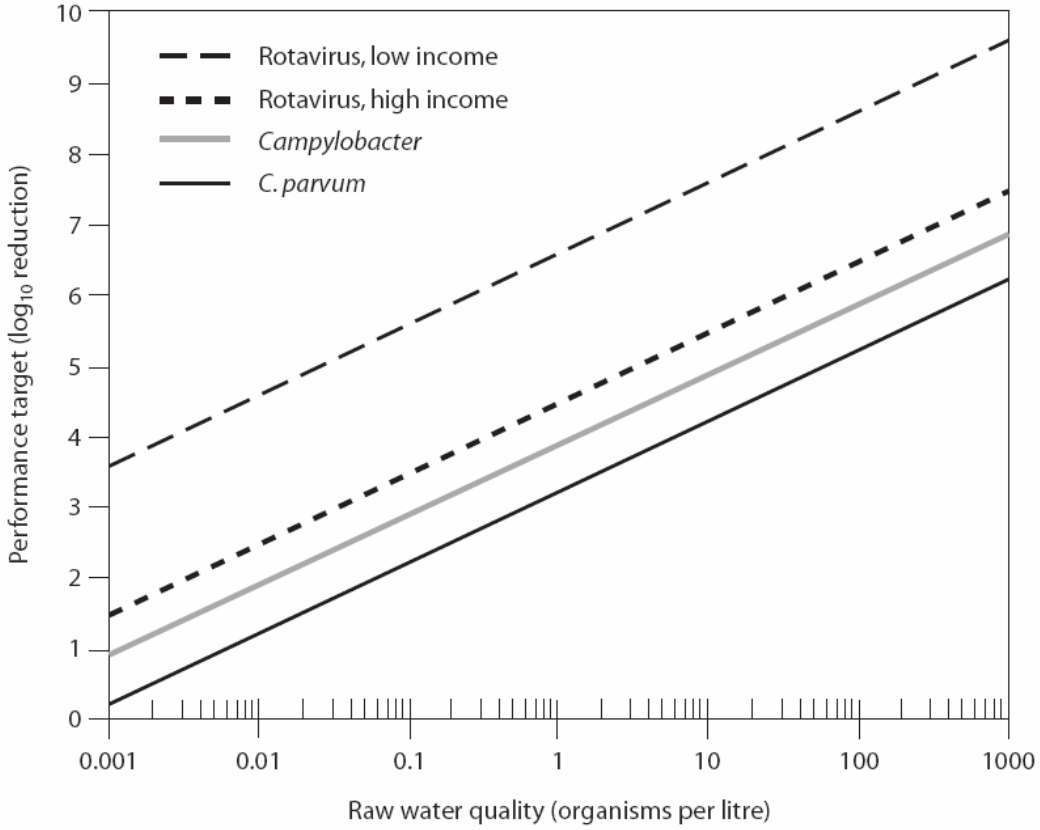


Table 7.4 Health-based targets derived from example calculation in Table 7.3

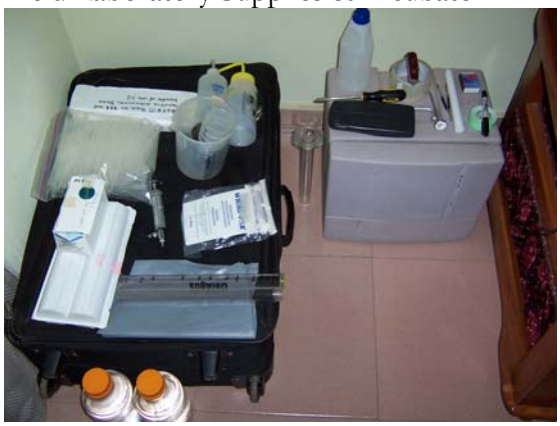
	Cryptosporidium	*Campylobacter*	Rotavirus[a]
Organisms per litre in source water	10	100	10
Health outcome target	10^{-6} DALYs per person per year	10^{-6} DALYs per person per year	10^{-6} DALYs per person per year
Risk of diarrhoeal illness[b]	1 per 1600 per year	1 per 4000 per year	1 per 11 000 per year
Drinking-water quality	1 per 1600 litres	1 per 8000 litres	1 per 32 000 litres
Performance target[c]	4.2 $\log_{10}$ units	5.9 $\log_{10}$ units	5.5 $\log_{10}$ units

[a] Data from high-income regions. In low-income regions, severity is typically higher, but drinking-water transmission is unlikely to dominate.
[b] For the susceptible population.
[c] Performance target is a measure of log reduction of pathogens based on source water quality.

Source: WHO (2006)

Appendix B – Field Study Photographs

Field Laboratory Supplies & Incubator



Foran (June 20, 2006)

Water Collection- Ghanasco Muali Dam

Foran (June 20, 2006)

St. Mary's Dam

Foran (June 29, 2006)

Vitting Dam

Foran (July 25, 2006)

Kaleriga Dam

Foran (June 22, 2006)

Bipelar Dam

Foran (June 27, 2006)

Dungu Dam

Foran (July 4, 2006)

Libga Dam

Foran (July 6, 2006)

Gbanyamni Dam

Foran (July 9, 2006)

Bunglung Dam

Foran (July 11, 2006)

Diare Dam

Foran (July 13, 2006)

World Vision Water Quality Laboratory

Foran (August 3, 2006)

Appendix C – Laboratory Photographs

Water Collection at Memorial Drive & Massachusetts Ave. [Foran (April 13, 2007)]

Appendix D – Field Results

Table D-1: Turbidity and Temperature Results for Field Experiments

Water Source	Turbidity [TU]		Post SolAgua Water Temperature [°C]
	Source Water	Post-Alum Admin	
Ghana School Dam	~1600	<5	52.2
Kaleriga Dam	>2000	<5	48.9
Bipelar Dam	38	~6	44.4
St. Mary's Dam*	>2000	<5	36.7*
Dungu Dam*	400	<5	36.7*
Libga Dam 1*	75	<5	47.8*
Bunglung Dam	300	<5	50.0
Diare Dam	23	<5	40.0
Libga Dam 2	50	<5	45.6
Gbanyami Dam	~1000	<5	26.7
Vittin Dam	~125	<5	40.0

*Cloudy/Overcast Day

Appendix E – Laboratory Results

Table E.1 General Results for Total Coliform Counts after 1, 2, 3 and 4 Hours under Low and High Intensity UV-A Radiation Conditions

Sample		Source Water [per 100mL]	TC (1 Hour)	TC (2 Hours)	TC (3 Hours)	TC (4 Hours)	Removal Efficacy (1 Hour)	Removal Efficacy (2 Hours)	Removal Efficacy (3 Hours)	Removal Efficacy (4 Hours)
Low Intensity UV-A Radiation	1	3,245	TNTC	TNTC	TNTC	139	-	-	-	95.7%
	2	1,543	TNTC	167	107	85	-	-	-	94.5%
	3	2,343	TNTC	TNTC	TNTC	90	-	-	-	96.2%
	4	4,145	TNTC	TNTC	TNTC	166	-	-	-	96.0%
	5	4,180	TNTC	TNTC	TNTC	82	-	-	-	98.0%
	6	2,407	TNTC	TNTC	TNTC	194	-	-	-	91.9%
	7	1,193	TNTC	TNTC	TNTC	60	-	-	-	95.0%
	8	6,275	TNTC	TNTC	TNTC	197	-	-	-	96.9%
	9	8,900	TNTC	TNTC	TNTC	195	-	-	-	97.8%
	10	2,068	TNTC	TNTC	TNTC	131	-	-	-	93.7%
High Intensity UV-A Radiation	1	9,650	TNTC	TNTC	TNTC	193	-	-	-	98.0%
	2	8,525	2070	535	140	118	75.7%	93.7%	98.4%	98.6%
	3	8,417	1100	162	52	13	86.9%	98.1%	99.4%	99.9%
	4	3,925	2000	500	143	83	49.0%	87.3%	96.4%	97.9%
	5	2,588	291	135	43	16	88.8%	94.8%	98.3%	99.4%
	6	1,303	200	120	29	6	84.7%	90.8%	97.8%	99.5%
	7	3,980	150	35	8	7	96.2%	99.1%	99.8%	99.8%
	8	10,450	93	37	18	6	99.1%	99.6%	99.8%	99.9%
	9	12,100	105	18	13	4	99.1%	99.9%	99.9%	100.0%
	10	2,217	190	39	24	14	91.4%	98.2%	98.9%	99.4%

Table E.2: General Results for Total Coliform Counts after 1, 2, 3 and 4 Hours under Low and High Intensity UV-A Radiation Conditions

Sample		Source Water [per 100mL]	EC (1 Hour)	EC (2 Hours)	EC (3 Hours)	EC (4 Hours)	Removal Efficacy (1 Hour)	Removal Efficacy (2 Hours)	Removal Efficacy (3 Hours)	Removal Efficacy (4 Hours)
Low Intensity UV-A Radiation	1	345	TNTC	TNTC	TNTC	1	-	-	-	99.9%
	2	215	TNTC	19	2	0	-	-	-	100.0%
	3	284	TNTC	TNTC	TNTC	2	-	-	-	99.3%
	4	360	TNTC	TNTC	TNTC	0	-	-	-	100.0%
	5	423	TNTC	TNTC	TNTC	1	-	-	-	99.8%
	6	343	TNTC	TNTC	TNTC	4	-	-	-	98.8%
	7	95	TNTC	TNTC	TNTC	0	-	-	-	100.0%
	8	717	TNTC	TNTC	TNTC	12	-	-	-	98.4%
	9	495	TNTC	TNTC	TNTC	12	-	-	-	97.7%
	10	292	TNTC	TNTC	TNTC	11	-	-	-	96.2%
High Intensity UV-A Radiation	1	2,260	TNTC	TNTC	TNTC	3	-	-	-	99.9%
	2	977	65	15	0	2	93.3%	98.5%	96.9%	99.8%
	3	623	35	4	0	0	94.4%	99.4%	100.0%	100.0%
	4	317	28	12	1	0	91.2%	96.2%	100.0%	100.0%
	5	100	7	3	0	0	93.0%	97.0%	100.0%	100.0%
	6	60	6	0	1	0	90.0%	100.0%	100.0%	100.0%
	7	142	17	0	0	0	88.0%	100.0%	100.0%	100.0%
	8	53	4	1	0	0	92.5%	98.1%	100.0%	100.0%
	9	53	1	1	0	0	98.1%	98.1%	100.0%	100.0%
	10	59	3	0	0	0	94.9%	100.0%	100.0%	100.0%