Point-of-Use Water treatment in Haiti

H2Eau
Haiti House of Water

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Table of Contents

Table of Figures

Table of Tables

1 Project Background

Access to clean drinking water is one of the world's most daunting development challenges. The United Nations Development Program estimates that 1 billion people today lack access to a safe, adequate water supply (Reed *et al.*, 2000). Clean water is essential to maintaining human health because waterborne pathogens cause diseases such as cholera, typhoid fever, and diarrhea (Cadgil and Shown, 1995). These pathogens usually originate from an infected host (either human or animal) and are transmitted by contaminated water through the fecal-oral route (Maier, 2000). There are over 800 million cases of diarrhea reported each year, of which about 5 million result in death (Wegelin, 1994). Waterborne diseases kill more than 400 developing world children every hour (Cadgil, 1995).

Waterborne diseases can be successfully controlled through the protection and treatment of water supplies. However, in the absence of treated water, people draw water from contaminated sources that contain the disease-causing pathogens such as bacteria, viruses, protozoa, and helminthes. Centralized water treatment facilities are common in developed countries but are considered too capital-intensive to be implemented in many developing countries (Cadgil, 1995). In addition, when such infrastructure does exist in developing countries, it is usually limited to urban communities.

1.1 Haiti

To provide a framework for our work in Haiti, we have researched Haitian history, culture, economics, environment, and religion. In addition, we have familiarized ourselves with the history and accomplishments of Gift of Water, Inc., an organization with which we worked closely. A summary of this information follows.

Haiti is both the poorest and most densely populated country in the western hemisphere (US Dept of State, 1998), and one of the poorest countries in the world. Eighty percent of the population lives below the poverty line (CIA, 2002), and seventy percent lives in rural areas (US Dept of State, 1998). Haiti has been plagued by political unrest for most of its history, and as a result lacks the resources for adequate water and sanitation infrastructure. Diarrhea is the leading cause of mortality in children under five years of age, with an incidence of 47 percent in 6-11 month olds (Pan American Health Org., 2002). As shown in Table 1.1, water related diseases are particularly common in rural areas where potable water is rare (USAID, 1985).

Table 1.1 Reported cases of water-related illnesses in 1980 (USAID, 1985)

		Diarrhea		Intestinal Infections		Typhoid	
Area	**Population**	**Cases**	**/1000**	**Cases**	**/1000**	**Cases**	**/1000**
Port-au-Prince	6,500,000	6608	10.2	4694	7.2	460	0.7
Gonaives	33,000	255	7.7	167	5.1	11	0.3
Port-de-Paix	15,000	455	30.3	2171	145	114	7.6
Hinche	10,000	694	69.4	738	74	100	10.0
St-Marc	23,000	851	37.0	314	13.7	266	11.6
Petit-Goave	7,000	294	42.0	1357	194	2	0.3
Belladere	25,000	875	350	272	109	68	27.2
Jacmel	13,000	320	24.6	152	11.7	87	6.7
North Dept.	560,000	3145	5.6	6819	12.2	141	0.3
South Dept.	500,000	1909	3.8	2380	4.8	462	0.9

Haiti encompasses 27,750 square kilometers in the west of Hispaniola, the largest island in the Carribean Sea. It is located roughly 600 miles south of Florida and 300 miles north of Venezuela, near the center of the West Indies. Haiti shares an island with the Dominican Republic, and is near Cuba, Jamaica, and Florida. It has two large peninsulas (Table 1.1), called the northern and southern claws, which are separated by the Golfe de la Gonâve. Haiti's current population is about 7.8 million people, with the largest population center at the capital, Port-au-Prince. It is both the poorest and most densely populated country in the Western Hemisphere. Haiti's natural environment contains a few remaining cloud-forested mountains and some fertile river valleys, but much of the countryside suffers from desertification and erosion.

Figure 1.1 Map of Haiti (Lonely Planet, 2001)

1.1.1 History

The modern history of Haiti begins with the first Columbus landing over five hundred years ago (Learning Network, 2001). Columbus and his crew promptly enslaved the native Arawak population, using them to mine for gold on the island of Hispaniola. Millions of indigenous died from disease, murder, and suicide. Estimates of the native population before European arrival range considerably: with an upper limit of 8 million and varying by at least an order of magnitude (Chomsky, 1993). By the time the French had taken Haiti from Spain in 1697, genocide lhad decimated the indigenous population.

To make up for the declining survival rate of indigenous peoples, the importation of African slaves began in earnest in 1519 (Chomsky, 1993). More than 800,000 slaves would be brought to Haiti from 1519-1549. As the gold and silver mines became depleted, slaves were put to work on agriculture and cattle farming for export to Spain. Towards the end of the 17th century, Spain ceded Haiti, or Saint-Domingue as its colonial residents called it, to the French. The French perpetuated the slave system instituted by Spain for nearly a century.

Fed up with slavery, and inspired by revolutionary events taking place in France, Haitian slaves began a rebellion in 1791 (Art of Haiti, 1996). After a vicious war, Haiti gained its independence on January 1, 1804 to become the first black republic in the world. When France departed, Haiti was left with no infrastructure and minimal health care. Water-borne diseases such as gastroenteritis became a significant health problem accounting for a significant fraction of adult deaths (Farmer, 2000). France recognized Haiti as an independent country in 1825 on the condition that the new government paid France the equivalent of $150 million for expropriated land in Haiti. Foreign debt would keep Haiti in economic hardship long after the French debt was paid in 1922 (Anarchy Inc., 2001).

The US began its series of interventions in Haiti as early as 1849 when US Navy ships entered Haitian waters. US ships would continue to enter 23 more times until 1913 (Chomsky, 1993). Two years later the United States began a 19-year occupation of the country. The occupation resulted in the deaths of 3,250 Haitians, as well as a change in the Haitian constitution. This change allowed for the foreign ownership of Haitian land. The occupation did create infrastructure in Haiti (e.g. roads, houses, hospitals). Yet the extent to which this helped the majority of the Haitian populace is uncertain as infant mortality reached 200-250 deaths per 1000 live births 20 years after the occupation ended (Farmer, 2000).

In 1957, Francois Duvalier became president of Haiti; his reign lasted until his death in 1971 (Chomsky, 1993). Duvalier's successor was his son, Jean-Claude Duvalier. The Duvalier dynasty was ripe with the stink of corruption. Repression, murder, and state brutality characterized the era. To bring money into Haiti, the Duvliers' sought to promote the country's comparative advantage in the manufacturing process (large labor supply and low wages). Thus in 1970, assembly plants began appearing in Haiti (Farmer, 2000). The change from agriculture to manufacturing was necessary after decades of deforestation and over-production had eroded the topsoil and reduced subsequent agricultural production.

Despite these neo-liberal initiatives, Haiti's debt increased, from 1973 ($53 million) to 1980 ($366 million) (Farmer, 2000). One reason for this may have been the graft apparent at the highest levels of government. The US Department of Commerce reported that 63 percent of government revenue was being misappropriated each year. A monthly average of $15 million/month was being used for "extra-budgetary expenses" which included payments to the president's Swiss Bank account. This theft did not help raise the standard of living of the Haitian populace. In 1976, 75 percent of the population was below the level of absolute poverty (less than $140 per capita).

As US support for Duvalier dwindled in the mid-eighties, popular movements against the regime became stronger (Chomsky, 1993). The ensuing political instability forced Duvalier's exile to France by 1986. In 1990, a catholic priest won an overwhelming majority of votes in what some observers noted was the first free and fair elections in the history of the country. Jean-Bertrand Aristide became president on a platform of land reform and taxation of the wealthy elite among other things. Seven months into his term, he was overthrown in a military coup. At this time, the under-five mortality was 137 deaths per 1000 live births, and 27 percent of rural population had access to safe drinking water.

The US occupied Haiti again in 1994 to reinstall Aristide as president (Farmer, 2000). In 1996, Aristide's successor, Rene Preval became president. Aristide returned to the presidency in November 2000. Throughout the Lavalas party's reign, they have been unable to significantly improve conditions for the Haitian population.

1.1.2 Culture

Haiti is the modern world's first black-led republic, and while its social, political, and environmental problems are well known, its culture is rich and unique. According to the Lonely Planet (2001)

> The language, dance and music of the Haitian people reflect a syncopation between the spiritual and material worlds that shouldn't be missed… Haiti's colonial architecture, all gingerbread and plazas, is alive with the music of Africa. Its surprisingly fine cuisine, of Caribbean ingredients prepared according to classical French methods, attracts gourmets from the other side of the island.

The national dance of Haiti is the *meringue*, a cousin of the Latin American version. Haitian music has been influenced by Cuban styles and American jazz. The country also has many celebrated painters, including Hector Hyppolite, LaFortune Félix, and Prefete Duffaut. Haitian painting is rich visually, often utilizing vibrant colors and sensual, organic forms (Lonely Planet, 2001).

1.1.3 Economy

Haiti is the poorest and most densely populated country in the western hemisphere (U.S. Department of State, 1998). However, the country's people are known for their sense of humor, possibly a requisite for survival (Lonely Planet, 2001). Population growth in Haiti is currently among the highest in Central America at 5 children per woman. Haiti has also been blamed as the source of HIV in the US, which caused the abrupt shut down of the Haitian tourism industry in the 1980's. Currently, 7 to 10 % of pregnant women in Port-au-Prince are HIV positive (Anarchy, Inc, 2001).

About 95 percent of Haitians are of African descent, with the rest of the population being of mixed African-Caucasian ancestry. French is one of two official languages in Haiti, but is spoken by only about ten percent of the people. All Haitians speak Creole, the country's other official language. Public education is free in Haiti, but private or parochial schools comprise about 75 percent of the educational sector. Only 63 percent of the Haitian population completes primary school (U.S. Department of State, 1998). Education is highly valued in Haiti, but most families can only afford to send their children to primary school because they are needed at home to help farm, keep house, and take care of younger siblings.

Seventy-five percent of the population of Haiti is involved in sustenance agriculture in rural areas, although urban migration to Port-au-Prince has increased over the last few years. Subsistence farmers, who rent or own a small plots of land, cultivate beans, sweet potatoes, and other crops using conventional farming technology. Most families live in small one or two-bedroom homes without electricity or running water and rely on charcoal as the principle energy source. In the cities, many end up living in densely populated shantytowns, void of civilian infrastructure such as water, electricity and sewage. Poverty is widespread, with over 75 percent of the country in "absolute poverty" (Lonely Planet, 2001).

Only one percent (mainly mulattos) of the Haitian population controls 44 percent of the country's wealth. These people mainly live in gated communities where fine restaurants and glittering shopping centers present a very different perspective of Haitian society. There are strong tensions between blacks and mulattos because of these inequalities. While the black population is an overwhelming majority (about 95%), mulattos have always been given the advantages in education, government and the military. This two-tiered social system is perhaps the greatest barrier to Haiti coming into its own as a stable and successful Caribbean nation (Lonely Planet, 2001).

1.1.4 Environment

The name Haiti comes from the Arawak word for 'mountainous land'. This name is more than fitting for Haiti as 60 percent of all its terrain is on gradients of 20 percent or steeper. The main mountain ranges in Haiti include the Massif de la Hotte on the southern claw, the Massif de la Selle, running west to east just southeast of Port-au-Prince, and the Chaine du Bonnet in the north. Additionally, numerous mountain streams burble down the hillsides, providing many mountain villages with freshwater. The only navigable river in Haiti is the broad Artibonite, which begins at the Dominican border and empties just north of St Marc (Lonely Planet, 2001).

Haiti also boasts astounding biodiversity, including 5000 plant species and 25 endemic bird species. However, only two mammals native to the island still survive in Haiti: the Hispaniolan hutia (mole-like) and the solendon (long-nose rodent). The abundance of biodiversity in Haiti is mainly due to the fact that its area includes nine distinct biomes ranging from sea level to mountains (Lonely Planet, 2001).

One of the most detrimental environmental issues facing Haiti is that of deforestation. Ninety-eight percent of the original tropical forest in Haiti has been deforested for export crops and fuelwood (Lonely Planet, 2001). Deforestation also has detrimental impacts on water quality because of increased erosion of the now-barren hillsides. Erosion has also been the major cause of loss of rich topsoil to the sea, where it chokes the reefs and marine life. However, there are four national parks established in Haiti to preserve what is left of the remaining virgin forest: Forêt des Pins, in the southeast next to the Dominican border; Parc La Visite, with limestone caves and rainforests 40km southwest of Port-au-Prince; Parc Macaya, at the western end of Haiti's southern claw; and Parc Historique La Citadelle, in the center of the Massif du Nord, near Cap-Haïtien.

The climate of Haiti is generally hot and humid, with temperatures varying more over the course of a day than from season to season. Highs are generally around 30°C, while nighttime lows can reach 20°C (65°F). The summer in Haiti lasts from June to August, and can be slightly hotter than the winter, though temperatures drop markedly at higher elevations. Haiti also has a rainy season, which varies with region (in the north, October to May and in the south, May to October), and a Hurricane season, which usually lasts from June through September (Lonely Planet, 2001).

1.1.5 Assessment of Haitian water resources

Only four percent of the governmental budget is allocated for potable water projects in Haiti, accounting for 15 percent of the total budget for such projects (USAID, 1985). The additional 85 percent of the funding for these projects comes from external assistance. There are two main organizations responsible for managing water resources in Haiti. The Centrale Metropolitaine d’Eau Potable (CAMEP) is responsible for supplying water in the metropolitan area and the Service National d’Eau Potable (SNEP) is responsible for rural water supply. Both organizations disinfect their water supply with chlorine, but this treatment is irregular and unreliable. CAMEP supplies water to approximately fifty percent of its potential customers and SNEP supplies approximately 39 percent (USAID, 1985). The rest of the population relies on private Haitian water vendors, whose water is from unprotected sources and rarely disinfected, or other local water resources such as wells and surface water.

The amount of water in Haiti, including surface water, groundwater, and springs, is believed to be sufficient supply for the entire population (USAID, 1985). However, these resources are limited by lack of access and proper treatment. Groundwater is believed to be abundant, particularly in the coastal plains where it is easy to access (Table 1.2). Groundwater is generally of better quality than surface water, for as water seeps through the soil to the water table, many microorganisms are removed (Lehr, 1980). Additionally, water quality often improves with storage in the aquifer because conditions are not favorable for bacterial survival. A properly constructed well (in addition to proper collection and storage methods) can ensure that the water remains clean and is safe for use.

Table 1.2 Groundwater potentials for selected areas of Haiti

Region	Number of Project Area	Number of Project Aquifers	Potential No. of Aquifers for which flow was estimated	Water flow (t/sec)
North and North Western Region	7	13	7	500-685
Artibonite Region	2	2	-	-
Southeast Coastal Region	3	5	2	399-1114
South Coast Region	5	3	2	530+
Central Plains Region	5	6	1	15-45
Total	22	29	12	1444-1844

Springs (places where groundwater has come to the surface) and surface waters are much more susceptible to bacteriological contamination than groundwater. Therefore, surface water should only be used when groundwater sources are unavailable or inadequate (Lehr, 1980). Surface water flow in Haiti is irregular, with short torrential flows during the rainy season and long periods of dryness - very few rivers have permanent flow (USAID, 1985). However, because groundwater in Haiti is often difficult to access, surface water and springs are the main water source for the Haitian people.

1.1.6 Religion

The main religion in Haiti is Christianity, predominantly Roman Catholic. A ten percent Protestant minority exists that has been converted by missionaries throughout the country (U.S. Department of State, 1998). In Haiti the church is the foundation of the community. The church often coordinates community infrastructure such as schools, government, and facilities. Therefore, the Haitian people have a very high respect for the church and work associated with them.

Haiti is also home to the often misunderstood, but beautifully spiritual *Vodou* (Voodoo). Vodou is a pantheistic African religion brought over by slaves. After missionaries persuaded the slaves to convert to Christianity maybe a little extreme? certain Catholic saints with attributes similar to those of the African spirits came to symbolize the same spiritual paths that had been venerated for generations. Therefore the two religions melded together so that the Catholic God came to be seen as responsible for "destiny" and the Vodou Iwa (spirits) responsible for the here and now. Present-day Haitians see no conflict between Vodou practices and Christian beliefs, and therefore practice both simultaneously (Lonely Planet, 2001).

Rituals commemorating the Iwa, lucky events, births, and deaths are a common practice in Vodou. These events involve dancing, drumming, and spirit possessions. Ceremonies are also performed to gain a certain Iwa's favor, perhaps to heal disease or end a run of bad luck, and may include offerings of food, toys, and even animal sacrifice. Other forms of prayer include the *veve*, a pattern made of cornmeal that pleases a specific deity, and the creation of colorful prayer flags, which are considered Haiti's finest form of folk art and collected worldwide. The music, drumming and dancing associated with Vodou rituals have now become an important part of Haitian pop culture (Lonely Planet, 2001).

Haitians believe in a number of different Iwa, descended from the various African countries of origin of the slave populations. Water is intrinsically tied to the Vodou relationship with the Iwa. The route to Iwa worship is through water because it is believed that the Iwa live beneath the water. Virtually all tales of human beings visiting the land of the Iwa describe them as descending into a river or disappearing into a waterfall. Water is therefore used to entice Iwa to ceremonies. It is spilled in a pathway in the service and used to call the cardinal points, and used to bathe (renew) the Iwa during the ceremony. In this regard, the baptism of Catholicism fits well with the water worship of the Iwa (Anarchy, Inc., 2001).

1.2 Gift of Water, Incorporated

One organization in Haiti that is helping rural communities obtain clean water is the US based Gift of Water, Incorporated (GWI). In 1995, the non-profit Industry for the Poor, Inc. (IPI), (now Gift of Water, Inc.) was created by Phil Warwick to work on water filtration in Haiti (Lantagne, 2001A). The organization worked with the Adopt-A-Village Medical Mission program in order to investigate epidemiological studies in Haiti (Anarchy, Inc., 2000). They discovered that chronic gastro-intestinal problems were common, most likely caused by the bacteriological pathogens that contaminated drinking water sources, including streams and wells. Industry for the Poor, Inc. conducted a cost analysis in order to begin development of an in-home gravity water filtration system intended to reduce the presence of bacteria and volatile chemicals in the drinking water.

The next year, a pilot program began in Dumay with 56 families purchasing purifiers (Industry for the Poor, Inc. 2001). In addition, 12 purifiers were donated to the University Hospital in downtown Port-au-Prince. There was a dramatic decrease in gastro-intestinal diseases, particularly in children, who are the most vulnerable. Industry for the Poor, Inc. hired and trained six local technicians in order to provide technical assistance to families using the filter. In 1997, a factory was built in Dumay to construct the filters locally (although the parts were produced in the U.S.) and the program expanded.

The filter apparatus costs US$15.29, but is subsidized by the program so that each family pays only approximately US$1.85 (Anarchy, Inc., 2000). Operating expenses for each filter, including chlorination and granular activated carbon, amount to approximately US$0.42 per year.

Since being approved by the Haitian Ministry of Health, filters have been placed in seven villages across Haiti (Lantagne, 2001A). Gift of Water, Inc. has provided filtration systems to serve over 22,000 people (Anarchy, Inc., 2000). Overall, the program has been deemed a success. With correct use of the filter, most waterborne pathogens are destroyed. The filters and associated education are assumed responsible for a 90 percent drop in water-related diseases in children under-5, according to information collected by GWI. Trained local technicians in all villages help assure correct and consistent use of the filter.

1.2.1 Filter Setup

The Gift of Water, Inc. filtration system is comprised of two five gallon plastic buckets, stacked on top of each other, and two types of filters through which water passes (Figure 1.2). Both buckets are 36 cm high with a diameter of 28 cm. The top bucket contains a polypropylene filter through which water must pass before traveling through a check valve into the lower bucket. This filter is designed to reduce turbidity and remove suspended solids from the water. On the other side of the check valve, attached to the lid of the bottom bucket is a granular activated carbon (GAC) filter, intended to remove chlorination by-products and other chemicals from the water. There is a spout on the bottom bucket to obtain water, as dipping unsterile cups into the bucket could cause contamination of the filtered water.

a) 

b) 

Figure 1.2 a) A full filtration system setup. b) The two filters used in the system, from left to right, the polypropylene filter and the granular activated carbon filter.

The water is chlorinated in both the top and bottom buckets. In the top bucket, 5 ml of 5.25 percent sodium hypochlorite solution (Clorox bleach) is currently added to approximately five gallons of water. A lid is placed on the bucket to prevent contamination and the bleach is allowed to act for half an hour. In Haiti, people are told to let the bucket sit for the amount of time it takes to cook a pot of beans (Lantagne, 2001A). After half an hour, the top bucket is placed on the bottom bucket and the check valve is opened to allow water to pass through the two filters into the bottom bucket. Five drops of bleach (0.2-0.25 ml) are placed in the bottom bucket in order to provide a chlorine residual to prevent the regrowth of bacteria and other pathogens. The water is considered finished and safe to drink after it has all passed into the bottom bucket.

1.2.2 Pathogens of Concern

There are four categories of pathogens that are of concern when discussing waterborne disease in humans: bacteria, viruses, protozoa, and helminthes (Table 1.3). Each class of pathogen contains many infectious species that can cause various illnesses. Of particular concern are those pathogens that induce diarrhea and vomiting, which can cause dehydration, a condition that is exacerbated by the fact that the water used for rehydration will most likely contain the same pathogens that caused the illness in the first place. This cycle can only be ended if water is properly disinfected.

Table 1.3 Pathogens associated with waterborne disease.

Organism	**Disease**	**Remarks**
Bacteria		
Escherichia coli	Gastroenteritis	Diarrhea
Legionella pneumophila	Legionellosis	Acute respiratory illness
Leptospira	Leptospirosis	Jaundice, fever (Weil's disease)
Salmonella typhi	Typhoid fever	High fever, diarrhea, ulceration
Salmonella	Salmonellosis	Food poisoning
Shigella	Shigellosis	Bacillary Dysentery

Vibrio cholerae	Cholera	Extremely heavy diarrhea, dehydration
Yersinia enterolitica	Yersinosis	Diarrhea
Viruses		
Adenovirus (31 types)	Respiratory disease	
Enteroviruses (67 types)	Gastroenteritis, heart anomalies, meningitis	
Hepatitis A	Infectious hepatitis	Jaundice, fever
Norwalk agent	Gastroenteritis	Vomiting
Reovirus	Gastroenteritis	
Rotavirus	Gastroenteritis	
Protozoa		
Balantidium coli	Balanticliasis	Diarrhea, dysentery
Cryptosporidium	Cryptosporidiosis	Diarrhea
Entamoeba histolytica	Amebiasis (amoebic dysentery)	Prolonged diarrhea with bleeding, abscesses of the liver and small intestine
Giardia lamblia	Giardiasis	Mild to sever diarrhea, nausea, indigestion
Helminths		
Ascaris lumbricoides	Ascariasis	
Enterobius vericularis	Enterobiasis	Roundworm infestation
Fasciola hepatica	Fascioliasis	Sheep liver fluke
Hymenolepis nana	Hymenolepiasis	Dwarf tapeworm
Taenia saginata	Taeniasis	Beef tapeworm
Taenia solium	Taeniasis	Pork tapeworm
Trichuris trichiura	Trichuriasis	Whipworm

(Metcalf and Eddy, 1991)

1.3 Point of Use Water Treatment

The GWI filtration program is one example of point-of-use water treatment in rural villages. Access to clean drinking water and adequate sanitation continues to remain one of the world's most daunting development challenges. The United Nations Development Program estimates that 1 billion people live without clean drinking water and 2.4 billion people lack sanitation facilities. In the absence of treated water, people draw water from contaminated sources that contain disease-causing pathogens such as bacteria, viruses, protozoa, and helminthes. Lack of clean water and the prevalence of unsanitary conditions lead to a high level of morbidity and mortality – 30,000 children die everyday from preventable causes such as diarrhea and other infectious diseases.

Centralized water treatment facilities are common in developed countries but are considered too capital-intensive to be implemented in rural Haiti. Low cost disinfection technologies are likely to be more feasible for the provision of safe drinking water in this context.

An appropriate point-of-use water purification system should fulfill the following criteria (Lehr et al., 1980, Shultz et al, 1984):

- Effective across a range of pathogens
- Robust to changes in water quality
- Effective in appropriate pH and temperature range
- Should not make water toxic or unpalatable
- Safe and easy to handle
- Must provide residual protection against possible recontamination
- Affordable
- Adaptable to local conditions
- Amenable to local production
- Appropriate to local culture and customs
- Comply with national sanitation standards

Current household disinfection mechanisms include boiling water, filtering, and chlorination. Boiling water requires firewood, the production of which is no longer sustainable in many areas of Haiti due to extensive deforestation.

2 Project Team Background

Haiti House of Water (H_2Eau) is a new company specializing in formulating optimal strategies for providing safe drinking water in developing nations, with a focus on Haiti. Our four-member team comprises a differential study specialist, Arun Varghese, solar disinfection (SODIS) specialist, Julie Parsons, and chlorination specialists, Michael Borucke and Sara Jo Elice. H_2Eau will work in conjunction with Gift of Water, Inc. (GWI).

Ms. Parsons' studies have focused mainly on the fate and transport of various substances (chemical and biological) in aquatic ecosystems. As an undergraduate, Ms. Parsons spent three months abroad studying the anthropogenic effects on water quality in Magdalena Bay, a major Gray Whale breeding ground on the Pacific coast of the Baja Peninsula. She has worked with various government, community and non-governmental organizations on water resource management issues, and gained a detailed understanding of the importance of considering the technical, social, and political aspects in conservation efforts. As part of her coursework, Ms. Parsons is studying the applicability of solar disinfection (SODIS) methods of water purification in developing countries.

Ms. Elice studied the biological need for chlorination in the drinking water in Haiti. While it is clear that disinfection is necessary for safe drinking water, it is unclear how much chlorination is necessary to effectively destroy pathogens. The goal of this study was to determine the minimum safe amount of chlorine addition to GWI's drinking water filtration system in order to assure safety while minimizing side effects of chlorination such as taste and odor. Ms. Elice has previously researched the effects of chlorination in drinking water as well as safe drinking water systems in developing countries, with a focus on Palawan Province in the Philippines.

Mr. Borucke investigated the ability of the GWI purifier to remove protozoan spores from drinking water in Haiti. The persistence of *Giardia* cysts and *Cryptosporidium* oocysts to traditional chlorination forces the sediment filter or the granular activated carbon filter to remove these pathogens from filtered water. Mr. Borucke has investigated wastewater treatment plants in Mexico and has taken several environmental microbiology classes.

Mr. Varghese has a multi-disciplinary academic background with a bachelor’s degree in chemical engineering and a master’s degree in economics and public policy. He has worked as an analyst of social infrastructure, housing, and microfinance policies in the developing world, and as a short-term consultant with the World Bank and the United Nations Population Fund. He has traveled in India, Africa, and Latin America.

H_2Eau believes that our company provided a strong team for the Point-of-use Household Water Treatment Project in Haiti. Our four members have considerable background in the issues in question, namely chlorination and alternative water disinfection and purification systems, as well as knowledge of the social repercussions of safe drinking water systems in developing nations.

3 SODIS

SOlar DISinfection (SODIS) is a simple water treatment method using natural solar radiation to inactivate pathogens commonly found in drinking water. This technology involves simply filling transparent PET bottles with contaminated water and exposing them to direct sunlight (Figure 3.1). SODIS utilizes the power of the sun to inactivate microorganisms using UV-A radiation and increased temperature. Because this technology is so simple, both in concept and application, it is easily applicable in the developing world where safe water resources are scarce. However, the success of SODIS is dependent on a number of conditions, including climate and water clarity.

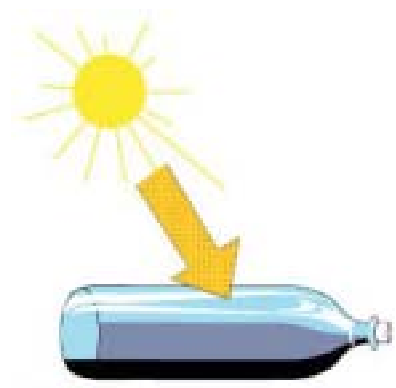

Figure 3.1 SOlar water DISinfection system

3.1 Mechanisms of Microbial Inactivation

The SODIS methodology utilizes both the infrared and ultraviolet spectra of radiation to disinfect water. The infrared spectrum is absorbed to generate heat and increase the bottle water temperature, and the ultraviolet spectrum directly inactivates microorganisms. The infrared spectrum is usually defined as electromagnetic radiation with wavelengths above 1000nm (10,000 Å), and the ultraviolet spectrum is radiation with wavelengths between 4 and 400 nm (40-4000 Å) (Koller, 1952). However, the atmosphere absorbs all radiation of wavelengths less than 200 nm (Parrish *et al,* 1978). Typically the remainder of the ultraviolet spectrum is divided into three portions: UV-C (200 to 290 nm); UV-B (290-320 nm); and UV-A (320-400 nm) (Figure 3.2). Of these, UV-A radiation is most abundant at the earth's surface.

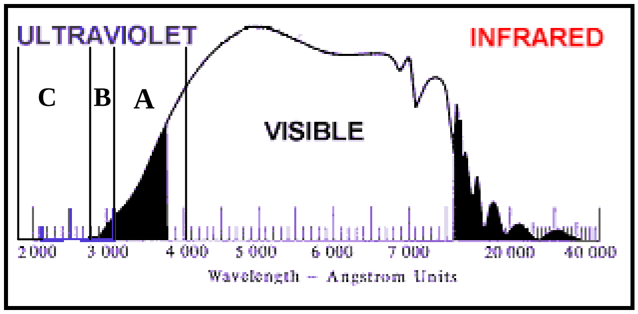

Figure 3.2 Electromagnetic Spectrum (Modified from PSU, 2001)

3.1.1 Thermal Inactivation

The first mechanism of disinfection utilized by SODIS is thermal inactivation of microorganisms. Microorganisms can only function within certain temperature ranges because of limitations of their metabolism. When these temperatures are exceeded, proteins and other macromolecules are denatured and the microorganisms lose their ability to function properly (Madigan, 2000). It is possible to disinfect drinking water without reaching boiling temperatures. This process, known as pasteurization, is different from sterilization in that sterilization inactivates all microorganisms, including heat-resistant spores. However, heat-resistant spores are harmless for humans to ingest, and thus pasteurized water is sufficient for drinking purposes. For *E.coli*, a pathogen causing diarrhea, pasteurization occurs above 70^{o}C (Wegelin et al,1994).

Microbial inactivation is also possible at temperatures below pasteurization temperatures. Between 20 to 40^{o}C, the inactivation rate of fecal coliforms remains constant (Wegelin et al, 1994). Above temperatures of 50^{o}C, microbial inactivation is enhanced through the synergistic effects of UV and temperature. At temperatures lower than 20^{o}C however, the thermal inactivation effects are negligible and therefore photobiologic effects (i.e. UV and photo-oxidative) are the main modes of disinfection.

The temperature of the SODIS system is increased by the absorbance of both long and short wave radiation by the bottle and the water, which then generates heat in the system. Some of this heat is re-emitted as back-radiation from the bottle into the atmosphere. Additionally, the system gains or looses heat through convective exchange with the air. The addition of wind can enhance convective exchange, thus increasing the rate of heating/cooling. In order to prevent rapid cooling, a wind-shield would be desirable to protect the bottles from heat loss, provided the shield does not shade the bottles. Additionally, uneven exposure can cause uneven heating, which causes a thermal gradient and induces circulation in the bottle (Wegelin *et al.*, 1994).

3.1.2 UV Induced DNA Alterations

Another inactivation mechanism of solar disinfection is the direct effects of UV induced

DNA alterations. Ultraviolet radiation is more biologically active than visible light because it is made of higher energy photons (Parrish *et al*, 1978). When photons are absorbed, all of their energy is transferred to the absorbing atom or molecule, which brings it to an excited state. While in this excited state, changes may occur in the molecule such as rotation, vibration, or changes to the orbital shells. Ultimately, photochemical reactions may be induced if the energy of the absorbed photon is greater than or equal to the activation energy required for a reaction. The typical activation energy for most biological photochemical reactions is between 40 and 100 kcal/mol, making UV light highly effective in causing photobiologic effects because of the amount of energy it contains.

The alteration of DNA molecules by UV radiation is the result of photochemical reactions within the cell. The peak amount of energy that can be absorbed by many bacteria corresponds to a wavelength of 260 nm, which is the maximum for absorbance by aromatic amino acid residues and their proteins (Parrish *et al,* 1978). Therefore, it appears that UV-C and UV-B radiation would be the most effective in the inactivation and killing of bacteria through photochemical alteration of cellular DNA. However, studies have shown that 10^4-10^5 times more UV-A radiation (either intensity or exposure time) can have the same inactivation effect as the lower wavelengths.

DNA exposure to UV radiation of lower wavelengths causes mutagenesis, resulting in death of the cell (Raven and Johnson, 1996). UV light absorbed by microbial DNA causes the covalent bonding of adjacent bases (commonly thymine-thymine, cystosine-cystosine, and thymine-cystosine), which form pyrimidine dimers (Figure 3.3) (Parrish *et al,* 1978). DNA replication is prevented by this mutation because nucleotides either cannot properly pair with the thymine dimers, or the dimers are replaced with faulty base pairs. If these mutations are perpetuated they prevent protein synthesis, which blocks metabolism and causes the organism to die.

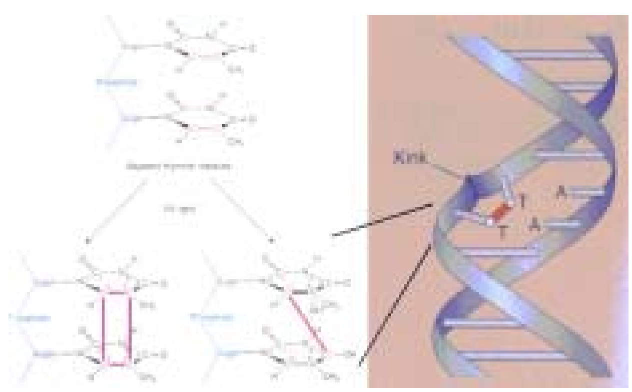

Figure 3.3 Formation of pyrimidine dimers in DNA

Additionally, hydrated pyrimidines, cross-linked DNA, DNA strand breakage, local disruption of hydrogen bonds, and changes to RNA can occur when cells are irradiated with UV (Parrish *et al,* 1978). All of these result in disrupted RNA synthesis and cell replication, likely resulting in death. Cell protein structure and enzyme activity are also affected by UV irradiation, but in comparison to the effects of DNA disruption, they are negligible.

Some microorganisms have adapted to UV exposure by the production of repair enzymes and protective pigments. In most microbial populations the resistant fraction comprises only 0.01 percent, though some studies suggest it can be as high as 10 percent for certain species (Kowalski and Bahnfleth, 2000). In cases of massive exposure, damage is too extensive for these mechanisms to repair. UV-A radiation has also been shown to damage these DNA repair mechanisms (Parrish *et al,* 1978). For example, the photoreactivating enzyme is both destroyed and activated by UV-A, and excision repair and single strand break repair mechanisms may be inhibited. Additionally, UV-A of about 365nm appears to alter active transport processes, proteins, and other enzyme activities.

3.1.3 Photo-Oxidative Disinfection

A third mechanism of disinfection that is utilized by the SODIS system is photo-oxidative disinfection. Highly reactive forms of oxygen, including oxygen free radicals and hydrogen peroxides, are formed in well-oxygenated water when exposed to sunlight (SANDEC, 2001). These species are so reactive that they can cause serious damage to living cells if formed in significant amounts (McKee and McKee, 1999). These reactive forms of oxygen inactivate microorganisms by oxidizing microbial cellular components, such as nucleic acids, enzymes, and membrane lipids (Reed, 1996). This damage results in enzyme inactivation, polysaccharide depolymerization, DNA breakage, and membrane destruction. These mechanisms either prevent proper cell replication or cause mutations, which are propagated through replication.

3.2 Required Conditions

3.2.1 Weather and Climate

The optimal region for use of SODIS is between 15^{o} and 35^{o} N latitude, a region characterized by high solar radiation and limited cloud coverage (the second most optimal region for SODIS is between the equator and 15^{o}N latitude) (SANDEC, 2001). It should be noted that the majority of developing countries lie within this region. According to SANDEC, within this region and during optimal weather conditions (less than 50 percent cloudy), the contaminated water needs to be exposed for 6 hours to achieve total disinfection. If the sky is more than 50 percent cloudy, or the bottle water temperature does not exceed 42^{o}C (necessary to induce synergistic effects), the bottle should be exposed for two consecutive days.

3.2.2 Turbidity

In order for SODIS to be effective, the water must be relatively clear (turbidity less than 30 NTU) (SANDEC, 2001). This is because suspended particles in the water can absorb solar radiation, thus reducing the depth to which solar radiation penetrates and protecting some microorganisms from radiation. Therefore, water with turbidity greater than 30 NTU would need to be filtered or bottle water temperature of $50^{o}C$ must be reached in order to achieve pasteurization.

In order to overcome the technical burden of exactly measuring turbidity, SANDEC has developed a simple method for determining whether or not water is suitable for SODIS. For this method, a full bottle is placed on top of the white SODIS logo in the shade. If the logo can be seen through the bottle, then the turbidity can be assumed to be less than 30 NTU. If the results are questionable, a higher turbidity should be assumed and the water treated accordingly (SANDEC, 2001). Such treatment may necessitate filtration, though usually allowing particles to settle and decanting the water off the top is sufficient.

3.2.3 Oxygen

In order to maximize the production of photo-oxidative species in the water, it is necessary to make sure the water is well aerated. In order to do this, one can shake the bottle when it is only half full, and then fill it completely (SANDEC, 2001). This technique should especially be applied to stagnant waters, such as from cisterns and wells. Reed (1997) recommends repeating this process hourly to ensure aeration is maintained. However, the effectiveness of this repeated agitation has been questioned by Kehoe, et al. (2001). They found that repeated agitation had no effect on the amount of inactivation achieved.

3.2.4 Container Material and Design

The most common type of container used for SODIS is PET (PolyEthylene Terepthalate) bottles. These bottles are preferred because they are commonly available, more lightweight and durable than glass, and are more chemically stable than other plastics. However, glass bottles have higher transmittance than plastic bottles (75 percent for glass versus 70 percent for plastic), so some transmittance is lost in using plastic bottles. Plastic bags have an even higher transmittance (90 percent), but are significantly less durable than either glass or plastic bottles and are also difficult to use. One significant drawback to the use of these bottles in comparison to glass is the rate at which they age due to mechanical scratches and the production of photoproducts, which leads to a reduction of UV transmittance (SANDEC, 2001). Because these bottles are commonly available in the developing world, this is not considered a significant problem because aged bottles can be easily replaced.

Another concern with the use of PET bottles is the possible formation of photoproducts on the plastic material as a result of UV-irradiation. These photoproducts are the result of the migration of additives out of the material, such as the UV stabilizers that are used to increase the plastics stability (SANDEC, 2001). However, in PET these additives are used less than in PVC (less than one percent of the PET components). Laboratory and field test addressing this concern have shown that these products are generated only on the outer surface of the bottles, and no migration into the water was observed.

In addition to the container material, one must also consider the size and shape of container most effective for SODIS. Because UV radiation attenuates with depth (50 percent attenuation at 10 cm with turbidity of 26 NTU), containers with a large exposed surface area to volume ratio are recommended. PET bottles used for SODIS have a sub-optimal shape because this ratio is small (SANDEC, 2001). With a water depth of 6-10cm, the water is not as evenly exposed to radiation as in a flatter container, such as a bag. However, this uneven exposure can cause uneven heating, which causes a thermal gradient and induces circulation in the bottle, which would ensure that each water parcel is exposed to direct radiation at some time (Wegelin *et al.*, 1994). Thus, although containers with a larger exposed area to volume ratio would be more efficient, in the developing world, one must learn to efficiently use whatever is available.

3.2.5 Limitations

Although SODIS seems to be the ideal solution for drinking water disinfection, as it requires no chemicals or technical expertise, it does have limitations. First, SODIS does not improve the chemical water quality, though studies are being undertaken to assess the effectiveness of UV-radiation in arsenic abatement, nor does it change the smell or taste of the water (SANDEC, 2001). The effectiveness of SODIS is also dependent on climate and certain water quality parameters, such as turbidity and dissolved oxygen, as discussed above. However, the user can easily adjust both of these parameters so that SODIS is effective (filtering/settling to reduce turbidity, mixing to increase oxygen). Additionally, SODIS offers only a very limited production capacity because of the limitations to bottle size/shape available, and therefore may not be a feasible solution for generating large quantities of clean water.

3.3 Research Goals

In order to assess the applicability of SODIS to colder climates, it is necessary to investigate possible ways of modifying the present system so as to make most efficient use of the available conditions. Though the area in which SODIS should be applicable based on the amount of available sunlight is very broad, some of the locations that fall within this region occasionally experience climate conditions not optimal for SODIS use due to elevation and seasonal variances. For example, the “winter” season has higher cloud cover associated with colder temperatures, during which SODIS may not be effective. Additionally, at higher altitudes, although sunlight intensity may be stronger, cloud cover is also much more common and temperatures much cooler.

Two possible methods to ensure that SODIS is effective under the conditions of lower temperatures and sunlight intensity are: 1) to enhance the heating capacity of the bottle or 2) to increase the amount of radiation incident on the system. The former can be achieved by painting the bottles with black paint, which absorbs solar radiation and converts it to heat energy. The later can be achieved through the use of solar reflectors to gather and focus UV onto the bottle. The purpose of this thesis was to investigate the effectiveness of both of these methods in sub-optimal climate conditions.

3.3.1 UV enhancement

Most metals are good reflectors for both visible and ultraviolet light (Koller, 1952). The efficiency of reflection depends on the cleanliness of the surface and absence of impurities. Aluminum is one of the most commonly used reflective metals because it is relatively inexpensive, easy to use, and resistant to corrosion. It is considered one of the most suitable for UV applications (Parrish, 1978).

The reflector used in this study consists of two parallel "slings" of reflective material supported by rope (clothesline) hung between two wooden base pieces (Figure 3.1). One reflector was built using aluminum coated mylar and another was built using materials that would be available in a developing country (aluminum foil supported by a plain brown paper). Each "sling" held three bottles end-to-end (for a total of six bottles per reflector).

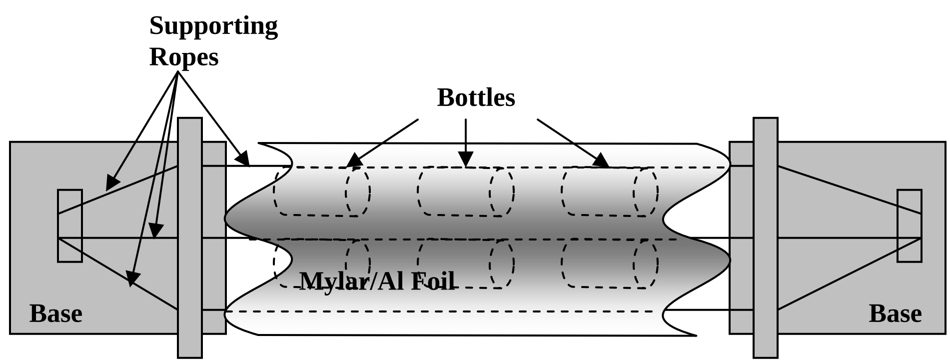

Figure 3.4 Top view of solar reflector used

3.3.2 Thermal enhancement

The recommended SODIS procedures call for painting bottles half black to enhance the heat absorbance capacity of the system (SANDEC, 2001). Theoretically, this increases the bottle water temperature by 5^{o}C by absorbing "extra" radiation. However, the amount of temperature increase is dependent on the available amount of radiation to be absorbed and the area and orientation of the surface painted black. This study investigated the thermal enhancing effects of painting bottles both half black and fully black to see if threshold temperatures could be reached despite low ambient air temperatures in areas where radiation is abundant.

The purpose of painting the bottles half black is allow for both thermal enhancement as well as UV disinfection, whereas the fully painted bottle will rely on thermal inactivation alone. Therefore the fully painted bottles must reach the threshold temperature of 50^{o}C to achieve disinfection. These temperatures were not necessary in the clear and half painted bottles because UV disinfection would be active in these bottles.

3.3.3 Bottle Water Temperature model

In addition to evaluating the above techniques for enhancing the effects of SODIS, this project also developed a mathematical model for the bottle water temperature under various conditions. Such a model would be useful for evaluating the suitability of SODIS in a particular locale and the techniques that should be used to enhance its effectiveness. The model is dependent on the local weather conditions over the appropriate period of time:

$T_a(t)$ = ambient air temperature [K]
$R(t)$ = total solar radiation [W/m^2]
$U(t)$ = wind speed [m/s]

There are four main heat flux components to this model: (1) heat generated by short-wave radiation absorbed by the system (Q_R), (2) heat gain through absorption of long-wave radiation (Q_L), (3) heat loss through long-wave radiation from the system ($-Q_b$), and (4) heat gain/loss by convection (Q_C). Therefore, at each time step the net heat flux into the system (Q_T) is the sum of these quantities:

$$Q_T = Q_R + Q_L + Q_C - Q_b \qquad \text{(Equation 1)}$$

This model cannot substitute for *in situ* field tests to evaluate the actual effectiveness of SODIS. These tests are still necessary to make recommendations for factors that are more site specific, such as exposure time and necessary water pre-treatment. However, the results of the model can predict whether thermal enhancement measures would be effective or not.

3.4 Research Outline

3.4.1 Location, Climate and Water Supply

Experiments for this study were carried out during the months of January, February, and March 2002. The month of January was spent conducting studies in two locations in Haiti: the rural community of Barasa and the more urban center of Dumay. Follow-up studies were then conducted throughout February and March in Boston, Massachusetts, USA. All of Haiti falls within the optimal latitudes for application for SODIS, and so the locations in Haiti were chosen based on their disparate weather conditions, which are due mainly to differences in elevation.

3.4.1.1 Barasa

Barasa is located in the southeastern part of Haiti, near the border of the Dominican Republic. The elevation in Barasa is approximately 1,400 feet. This is a mountainous region, characterized by cooler temperatures but more intense solar radiation than Dumay. The daily weather conditions observed usually consisted of approximately half a day of full sunshine (though it varied between morning and afternoon hours) and half a day of partly cloudy or fully overcast skies. The average daily ambient air temperature peaked at about 28^{o}C, and radiation peaked at around 770 W/m^2.

Barasa is located in a rural area where there is no access to running water or electricity. Therefore the people in Barasa do not have access to treated water, except for a few families with the Gift of Water, Inc. filtration system. Their main water supplies are cisterns or a nearby spring, Soos San Louis. This spring is difficult to access, not only because of its distance from the community, but also because it is located at the bottom of a steep ravine. The spring is highly contaminated, mainly from the fecal matter of pack animals used to transport water back to community members' homes. The water used for this study was a combination of water from the spring and a nearby cistern. The average turbidity of the water was 5.8 NTU (Table 4.1), well below the 30 NTU recommended for SODIS to be effective.

3.4.1.2 Dumay

Dumay is located near the city of Port-au Prince, at the base of the "southern claw" of Haiti. Weather conditions are much hotter in Dumay because it is at a lower elevation (very near sea level) and does not benefit from the trade winds that cross the more mountainous regions. During the 5-hour duration of this experiment the sky was clear, there was little breeze, and sunlight was intense. The ambient air temperature peaked at 47^{o}C. Radiation measurements from this location are not available due to equipment difficulties, but have been assumed to be on the same order of magnitude of daily radiation in Barasa.

The water used for this study was collected directly from a local stream found running along the streets in a more rural section of the city. Downstream from the site of sample collection, women were found to be doing their laundry, implying that this is a common water source for the local community. Due to the number of poultry and other animals nearby, it can be inferred that fecal matter also contaminated the stream. The same aeration method as used in Barasa was applied during sample collection. The average turbidity of this source was 25.2 NTU, also below the threshold for effective SODIS application.

3.4.1.3 Boston

Boston is located at 42^{o}N latitude, outside the recommended region for SODIS. The source used for this experiment was the Charles River, which flows between the cities of Boston and Cambridge Massachusetts, and past the MIT campus where the experiments were conducted. Turbidity measurements are not available for this source because the equipment was not available. However, all samples did pass the SODIS water clarity test, described in Section 2.2.2.

The weather in Boston during the time of this study was typical for the winter season in the northern hemisphere. Cold (near freezing) temperatures were observed, peaking at 12^{o}C, and overcast skies limited available radiation to less than 400 W/m^2. Because temperature and radiation measurements were taken less frequently than in Barasa, however, the exact peak radiation is not known (Figure 4.3). Additionally, because experiments were carried out on the roof of a four-story building, it was also subject to a constant breeze, which caused additional cooling of the bottles.

3.4.2 Exposure and Monitoring

Nine different SODIS regimes (outlined in Table 3.1) were tested in Barasa. Duplicates were made of the bottles without a reflector and with the aluminum mylar reflector for quality control. Duplicates were not made of the bottles on the aluminum foil reflector due to lack of space. Each regime was tested over 5-hour, 1-day (7-8 hours), and 2-day (two 7-8 hour) exposure periods. Three complete sampling runs (including all regimes and exposure times) were completed, with the first day of the two-day exposure overlapping with the 1-day exposure.

Table 3.1 Overview of experimental SODIS regimes and their purposes

	Regime	Data label	Purpose
Without Reflector	Clear bottle	C-a	UV
	½ black paint	C-b	UV and enhanced temperature
	Fully painted	C-c	Enhanced temperature
Reflector 1: Aluminum mylar	Clear bottle	UV1-a	Enhanced UV
	½ black paint	UV1-b	Enhanced UV and temperature
	Fully painted	UV1-c	Enhanced temperature
Reflector 2: Aluminum foil	Clear bottle	UV2-a	Enhanced UV
	½ black paint	UV2-b	Enhanced UV and temperature
	Fully painted	UV2-c	Enhanced temperature

Only the aluminum foil reflector was used in Boston and Dumay because observations made in Barasa determined there was no significant difference between it and the mylar reflector. Therefore, only seven exposure regimes were tested in Dumay and Boston. Additionally, duplicate bottles were not used, but duplicate microbial samples were taken instead. Only one 5-hour exposure regime was completed in Dumay. Two complete sampling runs, plus additional 1- and 2-day exposures were completed in Boston.

Temperature data was collected from every bottle hourly in Barasa and Dumay, and at least three times a day in Boston. A CheckTemp electronic thermometer from Hanna Instruments, which has an accuracy of $\pm 0.3^{o}$C between –20 to 90^{o}C, was used for making these measurements. In order to prevent cross contamination during this process, the thermometer was rinsed with boiled water between samples. Ambient air temperature was also recorded each time bottle water temperature measurements were taken.

Radiation data was collected hourly in Barasa using a Kipp & Zonen Solar Radiation Measurement System. This device measures total solar radiation between the wavelengths of 300 to 2800nm, which includes most UV-B, UV-A, visible, and some infrared radiation. The instrument detects both incoming direct solar radiation and reflected radiation. It works with one percent accuracy between the temperatures of -40 to 80^{o}C. Radiation data was not collected in Dumay due to equipment malfunction, and was collected with the same frequency as temperature data in Boston.

3.4.3 Microbial Analysis

In order to evaluate the effectiveness of each exposure regime, it is necessary to determine the amount of microbial inactivation achieved. In order to do this, both treated and untreated water samples were analyzed using the membrane filtration test methodology. The indicator organisms used in this study were *E.coli* and Total Coliforms. These bacteria normally occur in the intestines of warm-blooded animals and are thus a commonly used indicator of fecal contamination (Maier, 2000). These organisms are also generally hardier than disease causing bacteria, and therefore their absence is a reliable indicator of the absence of other organisms of real concern. The culture media used was m-coli blue broth from Millipore Corporation, on which *E.coli* colonies grow blue and Total Coliform colonies grow red. Blanks were also run for quality control purposes using sterile water and the boiled water used for dilution. The plates were incubated for 24 hours in a non-electric phase change incubator. After 24 hours of incubation, the *E.coli* and Total Coliform colonies on each plate were counted and normalized to a 100mL sample by multiplying by the dilution factor.

3.5 Results

The conditions observed in Barasa were sub-optimal for SODIS application because of cool climate. None of the bottle water temperatures reached 50^{o}C necessary for thermal disinfection. However, solar radiation was abundant in Barasa, and exceeded the necessary 500 W/m2 for effective UV-related microbial inactivation. This would therefore account for the fact that more kill was observed in the clear and half-painted bottles, which were exposed to UV radiation, versus the fully painted bottles, which were not exposed to UV radiation.

The conditions in Dumay were ideal for the application of SODIS because not only was there abundant solar radiation, but the climate was warm as well. Both the half-painted and fully painted bottles exceeded the threshold temperature of 50^{o}C for the one-hour required. It is therefore not surprising that significant kill was observed in both of these bottles. Additionally, it can be assumed that the amount of available solar radiation was high, therefore also effecting significant kill in the clear bottle as well.

The conditions in Boston were again sub-optimal for SODIS application because of limited solar radiation and extremely cold temperatures. However, the trend in microbial inactivation was similar to that observed in Barasa. Significant kill was observed in the clear and half painted bottles, regardless of exposure time, implying that solar radiation was sufficient for bacterial deactivation, whereas there was no significant kill in the fully painted bottles.

3.6 Statistical analysis

In order to properly analyze the effectiveness of the different exposure regimes, two different statistical tests were used to detect trends in the data. The two tests used were the Mann-Whitney test and the 2-sample t-test. Ideally these tests are applied to large sample sets, which are more representative of actual conditions. Unfortunately, the amount of data collected in this study was limited and so the validity of this statistical analysis is questionable. Because the conditions in Boston and Barasa were similar in that they did not exceed the threshold temperature, the two data sets were analyzed individually and grouped. No statistical analysis was conducted on the data collected in Dumay.

Statistical analysis was used to evaluate a number of different parameters and determine which regimes were worthy of further investigation. Each test compares two sample sets. The first analysis compared the background microbial concentrations to the concentrations in the treated water of each regime. The purpose of this analysis was to determine if the amount of bacterial kill in each regime was in fact significant, and thus the regime could be considered effective for water treatment. The second analysis compared the clear and half-painted bottle regimes on the two reflectors to their counterparts without a reflector. This analysis was used to determine whether or not the reflector was effective in enhancing microbial deactivation. Finally, the clear and half painted bottle regimes on the two different reflectors were compared in order to determine if there was a significant difference in their effectiveness.

3.6.1 Evaluating the Effectiveness of Each Regime

Only the microbial concentrations in the clear bottle regimes (both with and without the reflector) and the half-painted bottle regime on the aluminum foil reflector were consistently statistically different from the background microbial concentration within a 95 percent confidence interval with 5-hours, 1-day and 2-days of exposure (Table 3.2). Additionally, all of the other half-painted bottle regimes had statistically significant microbial kill with 1 and 2-days of exposure. Therefore, it can be assumed that these regimes were most effective for microbial deactivation. With only 5-hours of exposure, the other half-painted bottle regimes had statistically significant microbial kill within an 80 percent confidence interval. Thus, these exposure regimes could also be considered effective. None of the fully painted bottle regimes in had statistically significant microbial deactivation.

Table 3.2 Statistically significant microbial kill

	Statistically significant microbial kill?					
	5-hour		1-day		2-day	
	Yes	***No***	***Yes***	***No***	***Yes***	***No***
No reflector						
Clear bottle	95%CI		95%CI		95%CI	
Half-painted bottle	80%CI		90%CI		95%CI	
Painted bottle		✓		✓		✓
Al mylar reflector						
Clear bottle	95%CI		95%CI		95%CI	
Half-painted bottle	80%CI		95%CI		95%CI	
Painted bottle		✓		✓		✓
Al foil reflector						
Clear bottle	95%CI		95%CI		95%CI	
Half-painted bottle	95%CI		95%CI		95%CI	
Painted bottle		✓		✓		✓

Overall, only the clear bottle regimes were consistently effective for microbial inactivation, regardless of exposure time (within those investigated). However, the effectiveness of the half painted bottle regimes seems to increase with exposure time, and it also seems to be enhanced by use of the solar reflectors.

3.6.2 Evaluating the Use of Solar Reflectors

Data was collected daily in Barasa to compare the amount of radiation incident on a bottle on and off a reflector. Calculations made from these measurements show that the aluminum mylar reflector increased the apparent sunlight intensity an average of 20 percent. According to the above evaluation, it appears that the reflectors do in fact enhance the effectiveness of microbial inactivation in the half painted bottles. However, statistical analysis shows that the microbial concentrations in the clear and half painted bottle regimes are not statistically different between the bottles on the reflector and not, within a 95 percent confidence interval. This analysis was conducted for each of the 5-hour, 1-day, and 2-day exposure data sets within the grouped Boston and Barasa data, as well as the two individual location data. Additionally, no statistical difference was detected between the microbial concentrations in the bottles on the two different reflectors.

3.7 Bottle Water Temperature Model

The bottle water temperature model developed as a part of this study was created using a Microsoft Excel spreadsheet. The average air temperature and radiation data collected in Barasa were used as the climatic inputs to the model, and so the outputs were compared to the actual bottle water temperature monitored in Barasa. However, the one-hour time step at which measurements were taken was found to be too large to achieve accurate calculations with the model, and so the data was interpolated at 10-minute time steps. Because the wind speed and direction was not monitored in Barasa, the speed was estimated to be approximately 3.8m/s from observations using the Beaufort scale. It was assumed that the wind direction was perpendicular to the bottles, which would thus overestimate the amount of convection occurring.

In general, convection was the limiting term to heat transfer in this model. Because convection is small, the surface temperature built up so that it was very close to the bottle water temperature, therefore limiting the rate of conduction, and creating an insulating effect. Additionally, because the long-wave properties of the plastic are unknown, the model was run both with and without these components. Neglecting long-wave radiation creates a better fit for the clear bottle model, but has little effect on the fit of the half-painted and fully-painted bottle models.

The model consistently overestimates the temperature. However, an underestimate of the bottle water temperature would be more acceptable for SODIS application. Modifying the transmissivity factors for the clear bottle can greatly improve the fit, but it is consistently too high, even when all short-wave radiation is ignored. Additionally, there is no logical basis for this change. It is believed that theses discrepancies are more likely caused by inaccuracies of the material properties than by oversight of additional heat components. Therefore, more research is needed to assess the actual reflective, transmissive, and emissive properties of the plastic in order to make the model more accurate.

3.8 Conclusions

3.8.1 Thermal Enhancement

Under sub-optimal conditions, there was no significant difference in the amount the bottle water temperature was raised in the half-painted or fully painted bottles. The bottle water temperature of the clear bottles was the same as that of the ambient air temperature. In Barasa, the peak temperature difference between the clear and painted bottles was 8^{o}C – greater than that expected from the literature. However, this only achieved a peak bottle water temperature of 38^{o}C, well below the thresholds mentioned above. In Dumay however, which has similar amounts of available solar radiation, a temperature difference of almost 10^{o}C was achieved, and the threshold temperature of 50^{o}C was exceeded in both painted bottles. The difference in the peak temperature achieved can be mainly attributed to the difference in weather conditions, which were cooler and breezier in Barasa, which would cause cooler bottle water temperatures.

In order to assess whether or not a thermal enhancement technique would be effective in a specific region, the local weather conditions (air temperature, wind, available solar radiation) must be known. In general, if the ambient air temperature does not reach 45^{o}C, it can be assumed that the painted bottle water temperature will not reach 50^{o}C.

Additionally, because there was little difference in temperature between the half-painted and fully painted bottle, bottles should only be half painted in order to also allow for synergistic effects with UV.

3.8.2 UV enhancement

The amount of microbial kill observed in bottles on either reflector was not statistically different from that of their counterparts not on a reflector, nor was there a significant difference in bottle water temperature. There are many reasons why the reflector may not have had a significant impact on microbial kill. First of all, the dimensions of the reflector were not optimized to the bottle size because the bottle size to be used in different locations was not known. Additionally, because of material lightness, it was easily misshapen by the wind, often causing partial shading of the bottles. Finally, the amount of ambient solar radiation may have been abundant enough that a 20 percent increase (i.e. 1100 W/m^2 versus 900 W/m^2) did not have significant effect.

Further studies are needed in order to properly evaluate the effective use of solar reflectors/reflective bottle backing. Possibly such enhancement techniques would be more obviously effective with shorter exposure times or lesser amounts of ambient solar radiation. In any case, the reflectors did not seem to inhibit microbial deactivation and when used properly can be used without concern of negative impacts on the system.

3.8.3 Summary

This study evaluated a number of different exposure regimes in non-tropical climates in order to determine which were most effective and worthy of further research. In general, the fully painted bottle regimes were not significantly more effective for reaching the required temperatures than the half painted bottles. Additionally, there have been numerous studies already conducted on the use of the clear and half painted bottle regimes without a reflector. Therefore, it is recommended that the primary focus of future studies focus on the use of such reflectors with the clear and half painted bottle regimes in non-tropical climates.

4 Chlorine Demand

4.1 Purpose of Study

The purpose of this study was to determine the chlorine demand in Haitian drinking water sources in order to establish the most efficient amount of chlorine to use in the Gift of Water, Inc. filtration system. Minimization of the amount of chlorine in the top bucket is beneficial in a number of ways, but enough chlorine must be added to ensure that pathogens of concern are destroyed. Since it is important to have a chlorine residual in water that sits for a time before being used, a reduction of chlorine in the bottom bucket was not investigated.

4.2 Chlorination

4.2.1 Germicidal compounds

The bleach used in the Gift of Water, Inc. filtration system is a 5.25 percent solution of sodium hypochlorite, which reacts in water to create hypochlorous acid, HOCl. HOCl dissociates to form hypochlorite ion, OCl^-, which is 40-100 times less germicidal than hypochlorous acid (White, 1986; Metcalf & Eddy, 1991). The ratio of the concentrations of the two species is dependent on pH and temperature.

Chloramines are produced when ammonia is present, and are significantly less germicidal than hypochlorous acid. There are three species of chloramines, which are collectively called combined chlorine: monochloramine (NH_2Cl), dichloramine ($NHCl_2$), and trichloramine or nitrogen trichloride (NCl_3). Trichloramine is virtually non-germicidal.

When referring to the amount of chlorine in a water sample, HOCl and OCl^- are collectively referred to as free residual. A measurement of chloramines is called combined residual. The addition of the two is total residual.

4.2.2 Available Chlorine

Available chlorine (Av Cl_2) is a phrase that was created in order to compare the potential oxidizing power of various chlorine compounds, and the term is used to describe the concentration of chlorine that is necessary to kill certain pathogens (White, 1999). It is thought of in terms of Cl_2 not Cl^+, and the abbreviation is Av Cl_2. The available chlorine in any chlorine compound is twice the amount of Cl^+ that is present.

Available chlorine can be thought of as the oxidizing percentage of the mass of a disinfectant, which can be calculated by dividing the molecular weight of Cl_2 by the molecular weight of the disinfection species.

4.2.3 *Chlorine Demand*

Metcalf & Eddy (1991) defines chlorine demand as "the amount of chlorine that must be added to reach a desired level of residual." Aside from reactions with ammonia species, sodium hypochlorite reacts with many other substances in water, including turbidity, total organic carbon (TOC), hydrogen sulfide, iodine, nitrite and heavy metals, particularly iron and manganese. These reactions reduce the amount of chlorine residual available for disinfection, which in turn increases the amount of sodium hypochlorite that must be added to water in order to meet the chlorine demand of the system.

4.2.4 *Breakpoint Chlorination*

Breakpoint chlorination refers to the process by which chlorine reacts with all oxidizable species up until the point where the reactions do not further consume chlorine that is added to the water. Chlorine has four stages of chemical reactions in a water sample. The point at which all additional chlorine added becomes free residual is called the breakpoint.

4.3 Pathogens

The scope of this study has been limited to bacteria that cause gastroenteritis, including *Shigella*, *Salmonella*, *Toxigenic E. coli*, *Campylobacter*, *Vibrio cholerae*, and *Yersinia* (White, 1986; Metcalf & Eddy, 1991). If there is confidence that the majority of the bacteria that cause gastroenteritis are destroyed, a large percentage of waterborne illness should be eliminated.

The effectiveness of chlorination on a pathogen can be represented by the Ct value. The "C" in the Ct values represents the chlorine concentration, usually expressed as mg/l, and the "t" in the Ct value represents the contact time, usually expressed in minutes, required to kill a percentage of a population at a specific pH and temperature (Bitton, 1999).

Based on the Ct values for the pathogens of concern, in order to eliminate a significant amount of risk in the half hour contact time used in the Gift of Water, Inc. filter, it is necessary to have an available chlorine concentration of 2 mg/l. A single unit of sodium hypochlorite is equivalent to 95.4 percent of a unit of Av Cl_2, so in order to create an available chlorine residual of 2 ppm in a system with no chlorine demand, it would be necessary to create a concentration of 2.10 ppm NaOCl, which takes 0.756 ml of 5.25 percent bleach. A safety factor of 2 should be multiplied by this amount in order to account for uncertainties in Ct values or variations in temperature and pH. In a chlorine-demand-free system it would be acceptable to use only 1.51 ml of bleach for adequate disinfection. This number must be increased proportional to the chlorine demand of the system.

4.4 Methodology

4.4.1 Field Work in Haiti

Field work for this study took place in Haiti during the month of January 2002. Sites were selected from among the villages within which Gift of Water, Inc. has established filtration programs. One to four water sources was studied in each village visited, and the number and type of sources varied from village to village (Table 4.1).

There were five different types of water sources examined in this study: groundwater wells, surface water streams, springs, cisterns, and captages. Captages are outputs of water that have been piped down a mountain from a spring. Individual sources will further be referred to by location and number, as shown in the table.

Table 4.1 List of sampling sites, type of water source, date sampled, and local name.

Site	Number	Type of Source	Date Sampled	Local Name
Dumay	1	Captage	January 15	Kapatage Bò Kay Rodrigue La, Pa Two Lwen Legliz Pastè Nathan
Dumay	2	Captage (same site as 1)	January 27	
Dumay	3	Captage	January 27	Tiyo Santral Dumay
Dumay	4	Groundwater Well	January 27	Pwi Nan Kafou Dival
Dumay	5	Captage	January 29	Bò Bòs Deli, Campêche
Fon Veret	1	Cistern	January 16	Rectory: Sitèn Pè A
Fon Veret	2	Surface Water Stream	January 17	Karetye
Barasa	1	Spring	January 18	Sous Sen Lwi
Bas Limbe	1	Spring into Stream (mixed water)	January 20	Koray
Bas Limbe	2	Captage	January 21	Konti
Karako	1	Groundwater Well	January 22	Basalin
Les Palmes	1	Captage	January 24	Tewouj
Les Palmes	2	Captage	January 25	Senak
Les Palmes	3	Cistern	January 26	Rectory: Sitèn Pè A

4.4.2 Methods Utilized in Field

Tests conducted in the field included sampling for free and total chlorine residuals as well as the investigation of six water quality parameters ammonia concentration, iron concentration, temperature, pH, conductivity, and turbidity.

4.4.2.1 Experimental Setup

At each site my experimental setup consisted of several Gift of Water, Inc. filter top buckets, containing polypropylene filters, filled with source water. To each bucket a different amount of bleach was added in order to determine how a range of bleach concentrations were affected by the chlorine demand of the water supply. When filled, each bucket held approximately 5 gallons of water. At the majority of sites, 4 top buckets were used with a 1ml addition, 3 ml addition, 5 ml addition, and 10 ml addition of 5.25 percent bleach. The Dumay 1 setup had a 2 ml addition bucket instead of a 3 ml addition bucket. The Dumay 2 and Dumay 4 setups lacked 10 ml buckets.

Each bucket was tested for the six water quality parameters and residual chlorine as described below, with duplicates conducted on every tenth sample. Testing was completed half an hour after the addition of chlorine, which is the amount of time Gift of Water instructs filter owners to wait before allowing the water to pass to the lower bucket. All tests were also conducted on a raw water sample.

In addition to the tests done on each bucket, one sample was chosen at random at each of the first ten sites to be tested for chlorine residual every 10 minutes in order to determine the variation over time of chlorine residual in a sample.

4.4.2.2 Chlorine Residual Testing

The chlorine residual readings were taken with a LaMotte 1200 Colorimeter, using the DPD method for chlorine residual measurement. Because several samples were expected to have readings higher than the detection limit of the instrument, 4 ppm, all samples were diluted with distilled water by 19:1 using a 10 ml graduated cylinder.

The colorimeter was calibrated once per week using LaMotte's Chlorine Standards for Model 1200. The instrument had been borrowed from Gift of Water, Inc. and had previously been calibrated with primary standards.

4.4.2.3 Water Quality Parameters

Ammonia testing was completed using Hach's "Test Kit Nitrogen Ammonia, Model NI-8, Mid Range 0-3 mg/l, Color Disc", which uses the Nessler method to determine the amount of ammonia in a sample. Iron analysis was conducted using a Hach "Test Kit Iron, Model IR-18, Medium Range 0-5 mg/l, Color Disc", which uses 1,10-phenanthroline to react with ferrous iron (Fe^{2+}) to produce a range of colors proportional to the concentration of Fe^{2+} in a sample. The accuracy of both test kits is subject to the color perception of the test reader, but generally is approximately ± 10% (Hach Single-Parameter Test Kits, 2002).

Temperature measurements were conducted using an Envirosafe Celsius Thermometer, an instrument that requires no calibration. The thermometer was dropped into each sample bucket and left for a minimum of 2 minutes in order to allow the thermometer to reach the sample temperature. This was done after all other tests on a sample were completed in order to avoid possible contamination of the sample from the thermometer directly entering the water.

pH and conductivity measurements were taken with Hanna Instrument's HI-9812 Conductivity, TDS & pH meter. This instrument is temperature compensated for conductivity and pH measurements from 0 to 50°C (Hanna Instruments, 2001). This instrument was calibrated once each week for both pH and conductivity.

Turbidity measurements were conducted using a LaMotte 2020 Turbidimeter, which was calibrated once each week using 1 and 10 Nephelometric Turbidity Units (NTU) standards.

4.4.3 Follow-up Laboratory Work

In order to further evaluate the data that was gathered in the field, follow-up laboratory work was conducted. Three types of experiments were conducted: the testing of Haitian water samples for chlorine residuals, stratification experiments, and TOC measurements.

4.4.3.1 Haitian Water Testing

The first lab tests that were conducted utilized Haitian water samples brought to the US in January 2001. Instead of 5 gallon buckets, beakers filled with 100 ml of sample water were used, and an equivalent proportion of bleach was added to each beaker to represent the 1, 3, 5, and 10 ml buckets. All samples were diluted with Q-water, highly purified water assumed to have little chlorine demand, in order to assure that chlorine concentrations were not higher than the machine could distinguish. Testing was conducted on a DU Series 600 Spectrophotometer using the DPD method for chlorine residual measurements.

Standards were created using bleach and Q-water. Standards were created each day that testing was conducted, and ranged from 0.014 ppm to 1.42 ppm of Cl.

4.4.3.2 Stratification Experiments

Stratification experiments were also conducted in the laboratory. These experiments involved artificially stratifying water so that a layer of slightly warmer and less dense water lay on top of cooler water. The stratified column was produced by filling a tank with 19-21˚C water, and then pouring over the top water that was 10˚C warmer. The warm water was passively poured by dribbling the water into a spoon on the surface of the cooler water. This method of adding the warm water to the water column kept the warm from plunging into the cool as would happen if the water were simply dropped onto the water surface in a single plume. The goal for the warmer layer was approximately 1˚C warmer over 1 cm of depth or another combination with a product equivalent to 1˚C-cm. In order to visually assure that stratification occurred, the warm water was dyed red. A stratified layer of approximately 5 cm was created, such that there was roughly a 0.2˚C change in temperature across the entire stratified layer.

A salt water solution, composed of NaCl, blue food coloring, and Q-water was created with the same density as 5.25 percent bleach, 1.076 g/cm^3, in order to emulate field bleach additions without bleaching out the dyes used for visualization purposes. Varying amounts of the bleach substitute were added to the tank either in a single plume release or by carefully spreading the solution across the surface of the water column, to determine the fate of the bleach substitute in the stratified water column.

4.4.3.3 TOC Measurements

Experiments were also conducted in the laboratory in order to test for the presence of TOC in Haitian water sources. At each site 60 ml glass bottles, pre-filled with 1 ml of hydrochloric acid, were filled with source water and capped at each site. The hydrochloric acid was intended to acidify the samples so that inorganic carbon would be converted to CO2, which could be sparged out of the sample during the testing procedure (Clesceri et al., 1989). Samples were stored in the dark at 4˚C from the time of collection to the time of testing.

During transport, the Les Palmes 2 sample bottle broke, so only thirteen samples were available for testing. Of those samples all were tested except Dumay 1, Dumay 3, and Dumay 5. Due to time constraints, these samples were not tested, as they were all from free flowing captages in Dumay, like the Dumay 2 sample.

Concentrations of TOC were determined in the laboratory using the Shimadzu Total Organic Carbon Analyzer Model TOC-5000, which uses the combustion/non-dispersive infrared gas analysis method (Shimadzu Corporation, Date unknown). For my experiments, I tested for non-purgeable organic carbon (NPOC, generally referred to as TOC).

A calibration curve was found for the instrument by running 0, 1, 2.5, 5, 10, and 50 ppm standards and fitting a linear calibration curve to the data. The readings of my measured samples were compared to the calibration curve to determine the equivalent concentration.

4.4.4 Discussion of uncertainties

It is important to recognize that there are uncertainties in the data and that all numbers can only be known with a certain confidence. For field chlorine data, the uncertainty was determined by taking duplicates on every tenth sample and finding the percent error on the duplicate measurements. The range of percent error on the field chlorine data points was 2.3 percent to 49.7 percent. The average uncertainty was 24%.

Uncertainty in the laboratory residual measurements was determined using the calibration curves derived from standard concentration bleach solutions. A linear trendline was found and all samples were compared to this trendline to determine their chlorine residual concentrations. The samples can be no more certain than the calibration curve to which they were compared. The uncertainty of the laboratory data was also computed using the percent error of two data points, this time the known concentration of bleach at a certain absorbance, and the concentration of bleach that the trendline would compute for the same absorbance. The uncertainty is an average of the percent error from several calibration curves taken over several days of experiments. The value is 21.5 percent, very close to the uncertainty of the field samples.

4.5 Results

4.5.1 Water Quality Parameter Data

The results from the five water quality parameters tested were similar across the villages in Haiti (except for temperature), but some varied by the type of source tested (Table 4.2).

Table 4.2 Water quality data for raw water at each site

Raw Water	**Type**	**Temp.**	**pH**	**Conductivity**	**Turbidity**	**Iron**	**Ammonia**	**TOC**
Site		**˚C**		**µS**	**NTU**	**ppm**	**Ppm**	**ppm**
Dumay 1	Captage	26	7.2	580	0.05	0.4	0.4	N/A
Fon Veret 1	Cistern	22	8.2	70	0	0.4	0.4	1.72
Fon Veret 2	Surface water Stream	17	8.3	300	2.8	0	0.1	1.26
Barasa 1	Spring	17	7.6	430	10.91	0	0	0.83
Bas Limbe 1	Spring into Stream	26	7.1	540	1.86	0.1	0.1	0.54
Bas Limbe 2	Fauceted Captage	24.5	8.0	200	1.09	0.1	0.4	0.66
Karako 1	Groundwater Well	27.5	7.6	560	0.48	0	0.3	0.97
Les Palmes 1	Captage	20	7.0	110	0.96	0.4	0.1	0.88
Les Palmes 2	Captage	23	7.2	470	0.52	0.2	0.3	N/A
Les Palmes 3	Cistern	20	8.0	40	0.3	0.4	0.2	22.51
Dumay 2	Captage	26	7.3	590	0.26	0	0	0.80
Dumay 3	Groundwater Well	25	7.5	570	0.27	0.4	0.4	N/A
Dumay 4	Captage	26.5	7.3	690	1.3	0.4	0	26.81
Dumay 5	Captage	25.5	7.3	580	0.31	0	0.2	N/A

The water ranged in temperature from 17˚C to 27.5˚C, with a mean temperature of 23.3˚C. The lower temperatures generally occurred in the mountainous areas of Fon Veret, Barasa, and Les Palmes, where the daytime ambient air temperatures can be as high as the temperatures in the lower altitude villages, but the nighttime air temperatures are significantly cooler.

The pH of the water samples ranged from neutral to slightly basic, 7.0-8.3. There does not appear to be a correlation between the village in which the sample was taken and the pH, however pH may be correlated to the type of water source. All free flowing captages had close to neutral pH values ranging from 7.0-7.3. Slightly higher pH values were found in the groundwater wells with a pH range of 7.5-7.6. The cisterns tended to be slightly basic with a range of pH 8.0-8.2. The fauceted captage had a higher pH than the free flowing captages, perhaps affected by the water sitting in a concrete structure until the faucets were turned on. The concrete captages and cisterns had higher pH, most likely due to the limestone in the concrete. Surface water streams and springs ranged in pH values.

Conductivity seemed to vary no matter where the sample was taken or the source type, with one exception. Cistern water had significantly less conductivity than most other water sources. This is logical because conductivity is caused by ions in the water, and a cistern simply collects rainwater and holds it until it is used. The water does not have a chance to mix with the environment and collect ions.

Turbidity ranged from 0.00 NTU to 10.91 NTU. The highest turbidity was in surface water streams and springs. All other sources had a similar range of turbidity, from 0.00 NTU to 1.09 NTU, which did not appear to correlate to the type of source.

Both iron and ammonia readings ranged from 0-0.4 ppm. The error on these readings, however, is large. The color wheel in the test kits for both parameters did not have a noticeable color gradient until 0.5 ppm, and therefore all readings below that amount were largely estimated. Essentially all readings could be considered to indicate a value of iron or ammonia in the range of 0-0.4, regardless of what the reading taken on site was. Depending on who was looking and the angle of the sun behind the color wheel, the values read off varied greatly within that range for a single sample. Therefore iron and ammonia concentrations are considered extremely small and based on these tests, most likely did not contribute greatly to chlorine demand.

TOC concentrations were fairly low in most water sources. The average concentration of TOC was 5.70 ppm. Two samples were significantly larger than all other samples, Les Palmes 3 and Dumay 4, indicating that TOC most likely played a significant role in chlorine demand at those sites. Without the two high samples, the average TOC value was 0.96 ppm. Interestingly, while Les Palmes 3 had the lowest chlorine residual measurements, Dumay 4 had some of the highest total chlorine residual measurements. The high concentrations at Dumay 4, in spite of high TOC concentrations, are due to an undetermined cause.

4.5.2 Chlorine Data

4.5.2.1 Contribution of Combined Chlorine to Total Residual

Despite the low readings of ammonia concentrations, chlorine residual measurements indicate that combined chlorine was produced in nearly all samples and on average accounted for 25 percent of the total chlorine residual in a sample half an hour after the addition of bleach. Combined chlorine was calculated by subtracting the free chlorine reading for a sample from the total chlorine reading.

The presence of chloramines is not fully supported by the ammonia concentration measurements taken at the sites. There could be at most one chloramine created for each ammonia molecule present in the water. Assuming the validity of the results of the chlorine test kit, the greatest ammonia concentration that could have been present in a water sample was approximately 0.4 mg/l. At the extremes of only monochloramine produced or trichloramine produced, the maximum concentration of chloramines in the water would range from 1.2-2.8 ppm. Combined chlorine measurements in the field were on average 4.58 ppm, larger than the maximum expected measurement based on ammonia concentration

The reason for this discrepancy is unclear, but it may be attributed to many causes, such as residues in the colorimeter tubes or a lack of accuracy in the use of either the ammonia test kit or colorimeter. The uncertainty of the field chlorine residual measurements, ±24 percent, can only account for the difference between measured combined chlorine concentrations and expected combined chlorine concentrations based on the concentration of ammonia, for field measurements up to approximately 3.7 ppm.

4.5.2.2 High Chlorine Residuals

4.5.2.2.1 Field Data and Theory

The chlorine residual measurements conducted in Haiti yielded a peculiar trend. In particular, many concentrations were higher than the value expected if the bleach were well mixed and there was no chlorine demand (Table 4.3). The 10 ml bucket at Les Palmes 3, in bold, is the only sample that did not exceed the expected concentration.

A possible explanation is that there is not complete mixing in the filtration system and more of the bleach than expected remains on the top of the filter, where water for sampling is poured off. This is extremely problematic because it is possible that even with high levels of bleach addition to the filtration system, water in some parts of the bucket may not receive a chlorine residual that is sufficient to destroy all pathogens of concern.

Table 4.3 Total Chlorine Residual Measurements in ppm of Cl+. Raw water readings greater than 0 are most likely due to interference from Mn4+ or non-dissolved pieces of DPD tablet.

Site	Raw	1 ml	2ml	3ml	5ml	10 ml
Maximum Expected (no chlorine demand)	0*	1.32	2.65	3.97	6.62	13.24
Dumay 1	0.45	15.8	10		14.2	24.8
Fon Veret 1	0.59	15.4		18.4	24.8	35.13
Fon Veret 2	0.58	11.2		8.8	10.4	17.6
Barasa 1	0.69	9.73		17.4	15	37.6
Bas Limbe 1	0.59	14.4		16.6	18	30.93
Bas Limbe 2	0.62	17.6		20.6	21.4	29.2
Karako 1	0.67	11.44		18.2	15.6	43.6
Les Palmes 1	0.63	11.2		13	12.6	17.5
Les Palmes 2	0.69	4		12	9.2	17.2
Les Palmes 3	0.06	1.75		5	7.33	**9.25**
Dumay 2	0.78	23		19.5	18.6	
Dumay 3	0.8	10		17	18	27
Dumay 4	0.82	18.5		28.75	20.83	
Dumay 5	0.78	20.5		18.63	21.75	22.25

It is possible to capture a portion or all of the dense bleach that is put into a sample if the water is vertically stratified, meaning that there are layers in water that have a gradient in density. This could occur in two ways: either the initial water density was not completely uniform, or the water became stratified due to warming between the time the bucket was filled and the bleach was added. In the field, the water samples collected most likely would not have been initially stratified because in general they came from a flowing source where mixing occurred. However, in the time between the collection of the water and the addition of bleach to the buckets, it is possible that the ambient heat in the air as well as the sun could have warmed the upper layers of the water enough to create the necessary stratification to hold up a portion of the bleach.

For the purposes of the calculations that follow, a time of three minutes will be used as an estimate between the time of water collection and the time of bleach addition. It is possible that this time was longer for some samples, which would only increase the amount of time in which the air and sun could act to produce stratification in the water samples.

Energy is transferred into and out of water through a combination of several fluxes including solar radiation, atmospheric radiation, back radiation, evaporation, and convection (Ryan, 1974). The sum of these fluxes can be called Φ_{net}, which represents the total energy input to the water per unit area, and can be expressed as the product of a surface heat transfer coefficient, K, multiplied by the difference between the surface water temperature and a so-called equilibrium temperature, the latter being the temperature at which there would be no net heat exchange. In the absence of more complete meteorological data, the equilibrium temperature can be approximated as the ambient air temperature. For the purpose of these calculations, the ambient air temperature will be estimated as approximately 92˚F or 33.3˚C.

If an average K of 50 cal/(cm^2-˚C-day) and the average water temperature of my samples, 23.3˚C, are used, Φ_{net} is 500 cal/(cm2-day), which is equivalent to 500 ˚C-cm/day or 0.35 ˚C-cm/min (Adams, 2002). The units on this number indicate that in 1 minute, 1 centimeter of water can increase in temperature by 0.35˚C. In the three minutes estimated between water collection and bleach addition, there could be a 1.05˚C change in temperature (ΔT) over the top centimeter of water, or a proportionally smaller fraction of that temperature change over a proportional larger depth, for example 0.21˚C over five centimeters.

This heat addition creates a density change in the water. Density (ρ) is related to the temperature (T) of water in ˚C through the following equation [Adams, 2002]:

$$\rho = 1 - 6.3 \times 10^{-6} * (T-4)^2 \text{ [g/cm}^3\text{]} \qquad \textbf{Eq. 1}$$

Therefore the change in density is related to the change in temperature through the following relationship:

$$\Delta\rho = (\partial\rho/\partial T) * \Delta T = -1.26 \times 10^{-5} * (T-4) * \Delta T \text{ [g/cm}^3\text{]} \qquad \textbf{Eq. 2}$$

Using the average temperature of my water samples (23.3˚C) and the average temperature change for one centimeter of water (1.05˚C), the value for $\Delta\rho$ for this one centimeter of water is 2.6 x 10^{-4} g/cm^3.

A comparison of the mass deficit of stratified water and the mass surplus of bleach can be made by the following equation:

$$|\Delta\rho| * V_w \geq (\rho_b - \rho_w) * V_b \qquad \textbf{Eq. 3}$$

where,

V_b = Volume of bleach added
V_w = Volume of water over which the density change takes place
ρ_b = Density of 5.25% bleach ≈ 1.076 g/cm^3
ρ_w = Density of water ≈ 1 g/cm^3 at 23.3˚C

In order for all of the bleach to be held up, the product of the volume of water that is warmed and the density change in that water must be greater than the product of the volume of bleach added and the increase in the density of bleach over the density of water. Based on the water density change calculated above, 2.6 x 10^{-4} g/cm^3, and a bucket diameter of 28 cm, the left side of this equation is equal to 0.16 cm^3. Therefore the maximum volume of bleach that can be held up due to stratification under average temperature conditions would be 2.0 ml.

When more than 2 ml bleach is added, a fraction of the volume of bleach can still be held up, at maximum 2 ml, and the rest will settle to the bottom of the bucket. This possibility is maximized if bleach is not simply poured into the water in a single plume, but spread around, so that not all of the bleach would sink to the bottom and that some would get caught up in the stratified layer.

Although the theoretical ability of the mixed layer to hold up the bleach is independent of the layer volume or depth, the depth will have an effect on how concentrated chlorine residuals are in the layer (Figure 4.1). Based on the average measured concentrations for each bucket, in relation to the theoretical chlorine-demand-free concentrations, the stratified layer would have been between 5 and 10 centimeters. If there were significant chlorine demand in the water, the stratified layer could have been smaller while still achieving the same concentrations of chlorine residual.

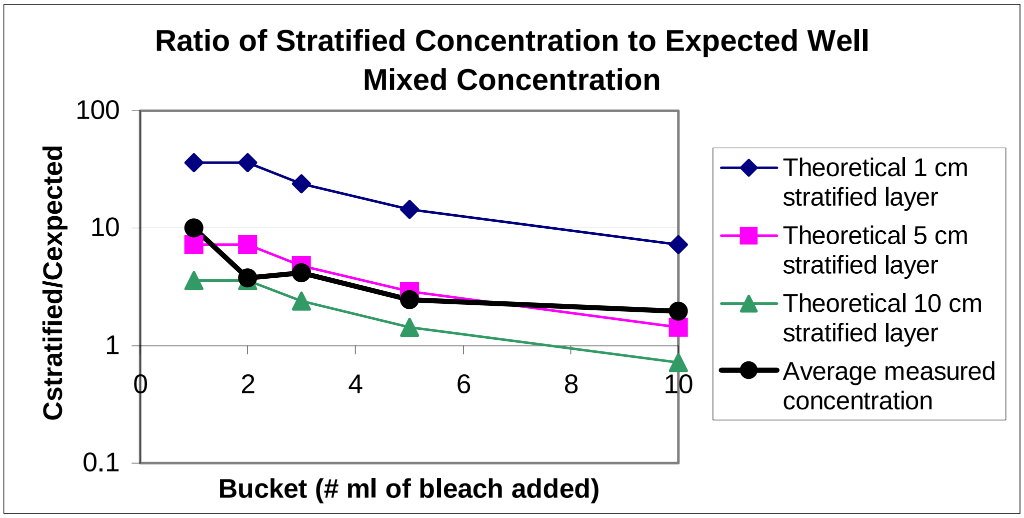

Figure 4.1 Comparison of stratified and well-mixed concentrations for varying depths of stratification.

4.5.2.2.2 Laboratory Stratification Experiments

The stratification experiments conducted in the laboratory supported the conclusion that 1 ml of bleach can be held up if there is approximately a 0.2˚C change over a 5 cm depth of water. A subsequent laboratory stratification experiment, in which 10 ml of bleach were dispersed into an artificially stratified water column, showed that the way in which bleach is dispensed can have an effect on how much bleach is held up. If 10 ml of bleach are added to the water in a single plume the stratification layer is quickly penetrated and mixing occurs throughout the water column as the bleach falls straight to the bottom of the column. In this case, relatively little of the bleach will be held up within the mixed layer. Alternatively, if the 10 ml of bleach is spread around the water surface, much more can get caught up in the stratified layer.

4.5.2.2.3 Laboratory Experiments and The Experience of Gift of Water, Inc.

The conclusion that the high concentrations of chlorine residual in the field were caused by stratification also appears to be supported by laboratory experiments that emulated, on a smaller scale, my field experiments on water samples brought back from Haiti a year earlier. A main difference between the laboratory setup and the field setup was that in the laboratory there was no sun, only fluorescent lighting, and the ambient temperature was significantly cooler, around 23˚C. There was still some energy transfer, particularly because the volume of water that had to be warmed to create stratification was less. However, most likely the flux of energy into the water was also less, so that a smaller volume of bleach could be held up, and the concentrations measured reflected this.

Gift of Water, Inc. most likely encountered this difference in the early implementation of its program. Lab work conducted by Phil Warwick determined that a safe level of chlorine addition to the filter was 3 ml of 5.25 percent bleach (Warwick, 2002). However, once the filter was utilized in Haiti, Gift of Water, Inc. observed that pathogens were surviving in the finished water. The amount of bleach added to the filter was raised to 5 ml and it was found that this level of chlorination provided sufficient disinfection. A likely explanation is that more bleach breaks through the stratified layer and falls to the bottom, mixing on the way down, with a 5 ml addition of bleach rather than 3 ml.

4.5.2.3 Lower Chlorine Residuals

The Les Palmes field samples generally produced lower chlorine residuals than other samples (Table 4.4).

Table 4.4 Les Palmes total chlorine residual measurements (ppm) compared to the average residual values for all field samples.

Site	1 ml	3 ml	5 ml	10 ml
Average across all sites	13.18	16.45	16.27	26.00
Les Palmes 1	11.2	13	12.6	17.5
Les Palmes 2	4	12	9.2	17.2
Les Palmes 3	1.75	5	7.33	9.25

The data indicate that there are two possible processes occurring, either separately or in combination. It is possible that there is something in the water in Les Palmes that is causing a significantly higher chlorine demand than other water sources have. There was nothing out of the ordinary in any of the water quality parameters, except TOC, however there may be another source of chlorine demand for which tests were not conducted, such as manganese (or TOC in the case of the Les Palmes 2 sample). TOC most likely played a large role in the low chlorine residual measurements of the Les Palmes 3 samples, as this site had a TOC concentration of 22.51 ppm, significantly higher than most other sampling locations.

Another possibility is that the Les Palmes samples were less stratified than samples from other villages due to differences in ambient temperature and solar radiation. There is reason to suspect that Les Palmes 3 has concentrations so much lower than other samples due to a difference in stratification, however there is no apparent reason why this would be so with the other two Les Palmes samples. Daytime sun and heat in Les Palmes seemed comparable to the sun and heat in other Haitian villages. Les Palmes 3, however, was sampled at 5AM, before the sun had risen and before the air had warmed to daytime temperatures (although the ambient temperature was still warmer than the water temperature). For this reason, there would not have been much stratification and more of the bleach would have fallen to the bottom of the bucket than in other samples.

4.5.2.4 Time of Residual Formation

At each of the first 10 field sites, chlorine residual measurements were taken at 10-minute intervals in one bucket, chosen at random, to learn how time affects the formation of free and combined residuals. The changes in the concentrations of free residual and combined residuals over time seem related to breakpoint chlorination the oxidation reactions that take place between free residual and chloramines. Initially there is the formation of chloramines as well as free residual, however after a certain amount of time, free residual reaches a large enough concentration that it begins to further oxidize chloramines, which reduces the concentration of both types of residuals. In general, chloramines concentrations continue to be reduced over time, while free residual concentrations continue to be reduced (a sign of the oxidation reaction with combined chlorine) or stay stable indicating that most oxidation reactions have taken place, and free residual is no longer used up. Based on this data, it appears that free residual generally does not react to fully oxidize combined residual in the half hour contact time used in the Gift of Water, Inc. filter.

4.6 Conclusions and Recommendations

It appears that there may be a significant chlorine demand in some of the drinking water sources that are gathered by users of the Gift of Water, Inc. filtration system. This is evidenced by the lower than average chlorine residuals in the Les Palmes samples, as well as the comparison of free residual to combined and total residual in all villages, both after thirty minutes and over ten-minute intervals. Chlorine demand will most likely play an important role in determining how much of a reduction in bleach addition Gift of Water, Inc. can afford without sacrificing adequate disinfection.

Unfortunately, the fact that the bleach apparently did not mix uniformly in the top bucket means that I cannot provide an answer to how much chlorine demand is present in Haitian drinking water supplies, nor can I recommend lowering the amount of bleach added to the Gift of Water, Inc. filter without further studies being conducted. In the absence of well-mixed field samples, it is not possible to determine how much chlorine residual is present throughout the water samples during the thirty-minute contact, and therefore the residuals cannot be compared to the Ct values of the pathogens of concern.

The primary recommendation of this study is that Gift of Water, Inc. implement mixing in the top bucket. This could be achieved in one of two ways. One solution is to create a small paddle, which would be used to stir like a spoon, and would be sold with the filtration system. It would be best if the paddle were of the same plastic as the buckets so as not to introduce a new material that might react with chlorine or other substances in the water. This paddle should be for explicit use with the filtration system.

Another possible solution is to require the use of a third bucket, which would carry the water from the source, but not be the bucket in which disinfection takes place. Bleach should be placed in the Gift of Water, Inc. top bucket prior to pouring the water from the third bucket into the top bucket. The momentum of the water falling onto the bottom of the bucket should be sufficient to mix the bleach.

Although there might be concern about contamination of the water from the paddle, if stirring occurred immediately after adding bleach to the top bucket, any pathogenic contamination would most likely get destroyed in the thirty-minute contact time along with the pathogens already present in the water.

Mixing is the only way to assure that enough chlorine residual is present in all areas of the water that pathogens might be, and should be implemented as soon as possible. After mixing is employed, it will be possible to run a series of tests to determine the chlorine demand of the Haitian water supplies. A future study is recommended in order to achieve the initial goal of this study, reducing the amount of chlorine used in the Gift of Water, Inc. filter.

5 Filtration of Protozoa from Haitian Water

5.1 Introduction

This study investigated the GWI system's ability to remove *Giardia lamblia* cysts and *Cryptosporidium* parvum oocysts from drinking water. *Giardia* and *Cryptosporidium* are present in waters throughout the world and their resistance to chemical disinfection techniques requires that the sediment and/or granular activated carbon filters be able to remove (oo)cysts from the water. The manufacturers of the sediment filter (Eagle Spring, 2002) claim that the 1-micron nominal and the 1-micron absolute sediment filters—made of woven polypropylene fibers— capture all *Giardia* cysts (Warwick, 2002). However, the sediment filter currently used in the GWI filtration system is wound with polypropylene that has 5-micron nominal pore spacing. Because (oo)cysts vary in size between 3-12μm, it is important to understand the ability of these filters to remove (oo)cysts.

Lab experiments were conducted on both a scaled-down and full-size version of the sediment filter (5-micron nominal pore spacing) as well as a scaled-down version of the GAC filter. Filtration was carried out with pH values in the range of those measured in Haitian water.

5.1.1 Giardia lamblia

The protozoan, *Giardia lamblia,* is one of the most primitive eukaryotic single-celled organisms (Campbell, 2002). The *Giardia* organism is a parasite; it lacks a mitochondrion and so it cannot create its own energy. Their life cycle is relatively simple and consists of a cyst stage and a trophozoite stage. In the external environment, *Giardia* exists as a cyst. Cysts are also found in the small and large intestines of its host.

Giardia cysts are ovoid in shape; the dimensions among individual cysts vary from 7-10 microns in width and 8-12 microns in length (Campbell, 2002). Most cysts contain 2-4 nuclei, an axoneme which is a fibrillar bundle of flagella, and a median body.

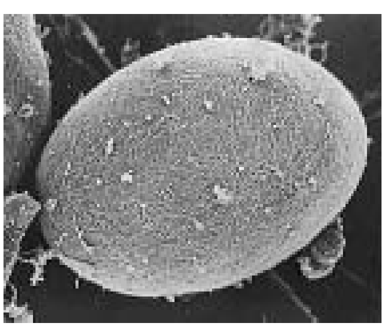

Figure 5.1: Field Emission Microscope scan of *Giardia* cyst (University of Minnesota, 2001)

Figure 5.2: *Giardia*: trophozoite stage (National Institutes of Health, 1998)

The thickness of the cysts wall is between 0.3-0.5μm. Ward et al. (1985) found that chitin was a major structural component of the walls of *Giardia* cysts (Fig. 5.1). Liu et al. (1994) demonstrated the resilience of chitin to chlorine.

Once inside the host organism, excystation occurs as the cysts break open (Campbell, 2002). Five to thirty minutes after excystation, cytokinesis occurs, and the cell divides into two trophozoites (Fig. 5.2). Trophozoites have two nuclei at the front end of the body and four pairs of flagella. Covering both body and flagella are variable surface proteins. The trophozoite can reach lengths between 9 and 21 microns when flagella are included. Infection occurs when trophozoites attach to the epithelial cells of the small intestine. The trophozoites reproduce by simple binary fission, occasionally producing cysts, which are passed along in the waste of the host into the environment. An infected person may pass millions of cysts each day. The principle vector of infection is water.

5.1.1.1 Giardiasis

The gastrointestinal illness that occurs as a result of *Giardia* infection is known as Giardiasis (Keas, 1999). Symptoms occur 1-2 weeks after infection and they include diarrhea, abdominal discomfort, nausea, and vomiting, among other things (Girdwood, 1995). An infection of a large number of trophozoites may lead to physical blockages of nutrient uptake, including A, B12, and D-xylose vitamins. Among healthy persons, the illness is usually short term, with a duration ranging from days to weeks. Among more vulnerable populations, Giardiasis can be fatal. This higher risk group includes children, the elderly, pregnant woman, and people with compromised immune systems, including persons that are HIV-positive. Giardiasis can also stunt the growth of children.

People may carry the cysts but may not become infected. Asymptomatic infection may also occur, where the infected person does not show symptoms of infection.

5.1.1.2 Global presence

There are approximately 200 million reported cases of giardiasis worldwide every year (Campbell, 2002). *Giardia* is present in waters throughout the world, in both developing and developed nations alike. In the United States, *Giardia* is the most common intestinal parasite with 2.5 million cases of infection reported annually. In addition, *Giardia* has been observed in South America, Asia, Africa, Europe and Australia.

5.1.2 Cryptosporidium parvum

Cryptosporidium parvum is also common in water-bodies; and while *Giardia* is often the cause of the most outbreaks of gastrointestinal disease, *Cryptosporidium parvum* often causes the most severe outbreaks (Addiss et al., 1995). In 1993, the largest outbreak of Cryptosporidiosis—an illness with symptoms similar to those associated with Giardiasis—in the United States occurred in Milwaukee, Wisconsin. An estimated

403,000 people out of a population of 630,000 were either laboratory-confirmed for Cryptosporidiosis or showed symptoms of infection including watery diarrhea.

Cryptosporidium oocysts range in size from 3-5μm. While they are somewhat smaller than *Giardia* cysts (7-12μm), they use same method to contact the collector grains as *Giardia* cysts and the surrogate spheres used in this study. The charge on the surface of the oocyst is also similar to *Giardia* cysts at similar pH values. Therefore the microspheres used as surrogates for *Giardia* cysts are also used as surrogates for *Cryptosporidium* oocysts in this study

5.1.3 Protozoa in Haiti

There has been little investigation into the presence of (oo)cysts in Haiti. However, two reports found evidence of *Giardia* and *Cryptosporidium* in stool samples in Haiti. Pape et al. (1994) found 3 percent of the diarrhea cases in the study were attributable to *Giardia*, whereas 33 percent were attributable to *Cryptosporidium*. The sample group in this study did not reflect the general population at large as the individuals in the group were also selected for being seropositive for HIV.

In a study to evaluate methods for preserving stool samples, Nace et al. (1999) found *Giardia* present in at least 19 percent of the samples taken from people in Haiti. It is unclear from the study whether the people sampled were previously diagnosed with an intestinal infection (or showed symptoms of infection), or whether this sample was from the general population.

5.1.4 Risk Assessment

The concentration of *Giardia* in water bodies is often very low. The infective dose, however, is also low. Rose et al. (1995) suggested that the probability of infection from exposure to one (oo)cyst of *Giardia* and *Cryptosporidium* is 2 percent and 0.47 percent, respectively. Consequently, standards for such protozoa in drinking water are strict. The World Health Organization holds that there is no tolerable concentration for microbes pathogenic to human in drinking water (WHO, 1993). The GWI filtration system helps families to meet the USEPA and WHO standards for bacterial removal (USEPA, 1998). This study investigates whether the GWI filter meets the standards from protozoan removal.

5.2 Laboratory Setup

A bench-scale model of the GWI filter was used for laboratory testing (Fig. 5.3). The string used for the model sediment filter was 1/30th the length of the original filter. The string was wound in approximately the same pattern as the original filter, though tension in the string was not accounted for when making the bench-scale filter. Since pore size is dependent on string tension, it is advised that users in Haiti do not unwrap and rewrap the sediment filter (Warwick, 2002).

In the bench-scale model GAC filter, a mass of 5.51g was used in the bench scale filter. The bed depth of this GAC filter was 8cm. For the trial using 1 gram of GAC grains, the bed depth was 1.5cm. The diameter of the scale-down filter was 1.5cm. Further specifications for the model are outlined in (Lantagne, 2001B). The carbon used came from GWI, so it is the same carbon used in Haiti filters.

Figure 5.3: Bench-scale model. Sediment filter (left) and GAC filter (right) were tested separately.

Several modifications to the original bench-scale model were needed for the following study. The string and GAC filters were separated so that breakthrough volumes and removal efficiencies for each filter could be obtained. Also, a separatory funnel of 1000mL volume replaced the 60mL funnel that sat atop the GAC filter. This change allowed for a more continual flow of water during testing and would not otherwise affect results.

5.2.1 Polypropylene String

The polypropylene string wound around the core has no charge (Eagle Spring, 2002). The filters used by GWI are 5-micron nominal filters: approximately 50 percent of the pores are equal to or greater than 5-micron. The thickness of one fiber of the polypropylene string was measured to be 50μm ±10μm using an ocular eyepiece with an order of magnitude magnification. It is questionable as to whether particles an order of magnitude smaller than 50μm can be removed with such a filter.

5.2.2 Granular Activated Carbon

The granular activated carbon is a 12/40 bituminous coal-based carbon and it is imported by American Carbon, California, from several different countries (Turquand, 2002). The size of carbon pellets used in the filter range from 0.6-2mm and the densities range from 0.48-0.52 g/mL according to the manufacturer.

The porosity of the GAC was determined empirically by adding water to a known volume of GAC. A volume of 22mL of GAC and air in a graduated cylinder was saturated as 13mL of water was added, therefore the empty space in the GAC is 13mL/22mL = 59%. The GAC was not packed down which may lead to an overestimate of porosity as it applies to the GWI system.

5.2.3 Surrogates

For this study, Fluorescbrite Microspheres® were used as surrogates for both *Giardia* cysts and *Cryptosporidium* oocysts. The use of surrogates was done primarily for safety reasons during lab work. The latex microspheres were made of polystyrene and coated with a fluorescent dye (Polysciences, 2002). This particular category of microsphere had a carboxylate group attached to its surface. According to the manufacturer, there was 0.1-0.2mmol of carboxylate molecules per gram of beads. The average diameter of the microspheres was 5.7 microns with a standard deviation of 0.34 microns. They are manufactured by PolySciences and were delivered in an eyedropper-sized bottle in a 2mL, 2.5 percent water suspension.

The influent concentration used in trials for this study was a 1:1000 dilution or $1.13\text{x}10^5$beads/mL. All effluent samples were examined using a Perkin Elmer LS50B Luminescence Spectrofluorimeter, hereafter called a fluorimeter. A sensor in the fluorimeter is situated such that it receives light emitted from the beads at an angle orthogonal to the incident light. A computer program then plots the intensity of light detected as a function of the wavelength of that light.

5.2.4 Haitian Water

Observed values of pH in Haitian water ranged from 7.0 to 8.3. The pH of the Q-water was consistently in the range of 4.0-4.5. The addition of 0.2 grams of $NaHCO_3$ per 1L increased the pH to 7.0 and 0.6g per 1L increased the pH to 8.5.

5.3 Results

For all runs, influent concentrations were taken from the bucket before filtration began. This was done to account for microspheres—hereafter referred to as spheres—that may have stuck to the sides of the bucket or container. It is assumed that the water in the bucket was well mixed at time of sampling. All samples were run three times to obtain an average concentration. Concentrations of 0.2g/L and 0.3g/L of sodium bicarbonate were used to obtain pH values of 7 and 8.5, respectively. These were the extremes of the pH values measured in Haitian water (Table 5-1). Temperature of the Q-water was nearly constant throughout the experiment ($22^{o}C \pm 1^{o}C$). This is approximately the median temperature in the range of temperatures measured in Haiti.

5.3.1 Bench-Scale GAC Filter

The GAC filter tests were carried out after the carbon had been flushed with water at the appropriate pH. Two tests used approximately 5.5g of carbon and were conducted at pH 7 and 8.5, respectively. A third test used 1g at a pH of 7 to determine if that amount would become saturated within a smaller volume.

5.3.1.1 Bench-Scale GAC Filter, pH 7

The test at pH 7 was conducted over a period of four days. Effluent samples had a 30 percent breakthrough immediately after the start of filtration (Fig. 5.4). On the first day of testing, approximately 2.5 liters of solution were filtered through the GAC and a steady increase in effluent concentration was measured reaching approximately 50 percent of influent concentration. The filter dried overnight, as is the case for filters in Haiti, and additional volumes were put through the filter the following day. These volumes and the volumes on subsequent days displayed more variability in effluent concentrations, though the trend for the entire experiment was a general increase in effluent concentration to near 80 percent breakthrough.

Allowing the filter to dry out overnight (on the order of 13 hours) may have increased the removal rate of the spheres to the GAC. The third and fourth days of the test showed a decrease in the effluent concentrations for the first samples taken since the previous day. The concentrations soon increased to that of the previous day. However, for the first sample taken on the second day, the effluent concentration was statistically equal to the last sample taken on the first day.

5.3.1.2 Bench-Scale GAC Filter, pH 8.5

The test at pH 8.5 had an immediate breakthrough of spheres at approximately 60 percent of the influent concentration (Fig. 5.5). This test was conducted over a period of three days. Like the test at pH 7, the breakthrough gradually increased to 80 percent. Unlike the first test, this test showed less variability with the exception of an outlier at approximately 18.5 liters, which was ignored.

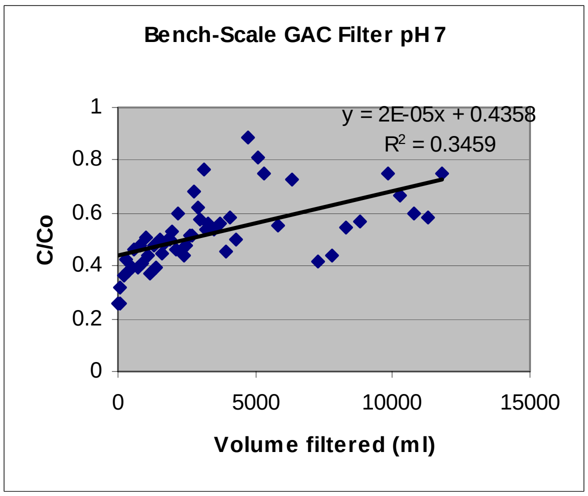

Figure 5.4: Bench-Scale GAC at pH 7

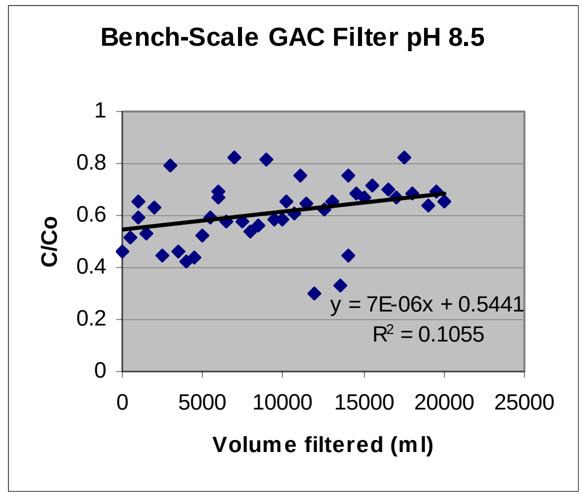

Figure 5.5: Bench-Scale GAC at pH 8.5

As expected from the modeling of packed bed filtration, the spheres rapidly broke through the GAC columns. This strongly suggest that the same would happened to (oo)cysts.

5.3.2 GWI Sediment Filter

For the full-scale, GWI sediment filter, three tests were conducted: one at pH 7, one at pH 8, and one in which the pH varied from 4.5 to 8. Two runs were conducted for the first two tests: a flushing run and a sphere run. The flushing run consisted of filtering water without beads at the appropriate pH. This run flushed out debris in the filter and provided a background electrolyte for the sphere run. The influent and effluent concentrations of the flushing runs were corrected by the blank concentrations. The additional intensity value (~3.7) was attributed to extraneous debris (non-sphere particles) in the water. There was no flushing run associated with the test in which pH varied from 4.5-8.5.

The influent concentration of the sphere run was corrected by subtracting the corrected influent concentration from the flushing run. Effluent concentrations of the flushing run were averaged and this value was subtracted from the effluent concentrations from the sphere run to obtain the corrected effluent concentrations for the sphere run. Finally, the corrected effluent concentrations were divided by the corrected influent concentration to obtain the percent of spheres that were not removed by the filter. The percent of spheres removed by the filter is obtained by subtracting this number from one.

5.3.2.1 GWI Filter Run at pH 7

Effluent concentration was greater than 50 percent immediately after the start of the run, and stabilized at around 80 percent for the remainder of the run (Fig. 5.6). The first data point was a sample taken immediately after the filtering began. The inconsistency of the first point with the rest of the graph could indicate initial filtering capacity or unmixed initial influent.

5.3.2.2 GWI Filter Run, pH 8.5

The effluent concentration was more than half of the influent concentration immediately after the beginning of the run (Fig. 5.7). The effluent concentration increased to approximately 80 percent for the remained of the run. There was no statistical difference in percent removal between this run and the run at neutral pH.

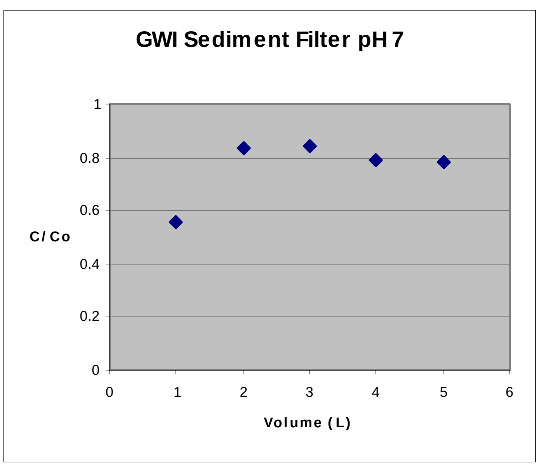

Figure 5.6: GWI Sediment Filter at pH 7

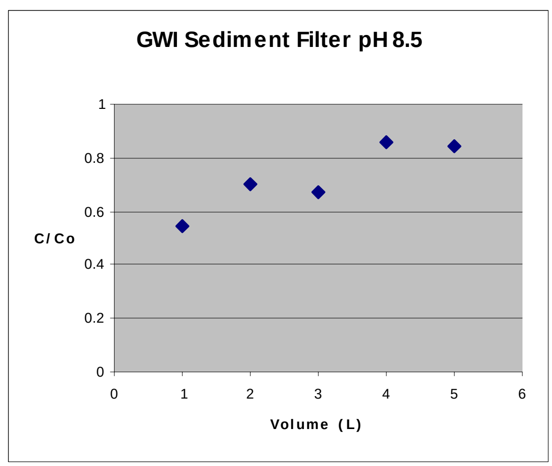

Figure 5.7: GWI Sediment Filter at pH 8.5

5.3.3 Bench-Scale Sediment Filter

Tests were carried out on the bench-scale sediment filter at pH 7 and pH 8.5, respectively. Water with background electrolyte was flushed through the sediment filter prior to testing. The background effluent concentration—obtained by measuring intensity of effluent water (pH 8.5) without spheres—was subtracted from the effluent concentration run with spheres to achieve an accurate effluent concentration. The second sample of background effluent without spheres was chosen as background effluent concentration since the first sample showed an unusually large concentration most likely due to residue from prior runs. The second sample was taken towards the end of the run and had a measured concentration close to the blank. The effluent concentration was then normalized by the influent concentration minus the background influent concentration and plotted against the volume filtered.

5.3.3.1 Bench-Scale Sediment Filter, pH 7

The influent and effluent concentrations were corrected by flushing blank water at pH 8.5. There was no correlation between intensity measured by the fluorimeter and pH. The immediate breakthrough was 100 percent and this was held constant throughout the run (see Fig.5.8).

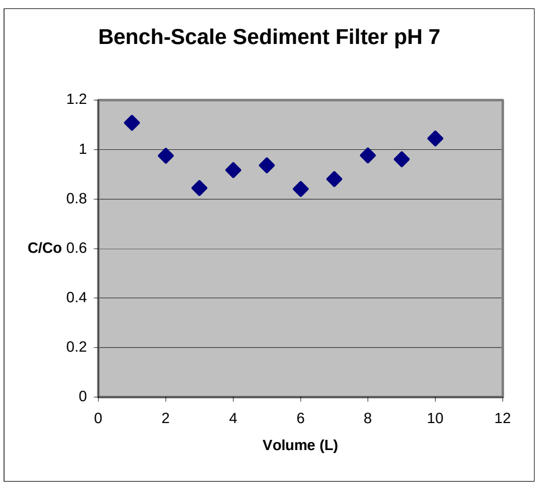

Figure 5.8: Bench-Scale Sediment Filter at pH 7

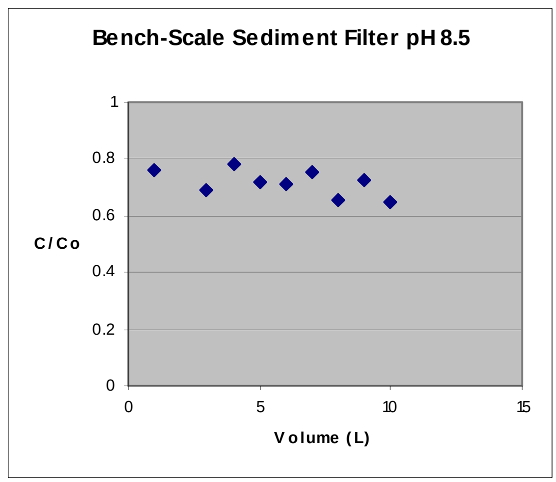

Figure 5.9: Bench-Scale Sediment Filter at pH 8.5

5.3.3.2 Bench-Scale Sediment Filter, pH 8.5

Several samples were taken for every liter filtered. The concentrations of these filters were averaged over each liter filtered, normalized, and plotted as outlined above (see Fig. 5.9). Immediate breakthrough concentration was near 70 percent, which gradually decreased as volume filtered increased.

The results for the bench scale GAC filter, the full-size GWI filter, and the bench-scale sediment filter are summarized in Table 5.1.

Table 5.0.1: Summary of Removal efficiencies for three filters

% Removal of surrogates	pH 7	PH8
GWI Sediment Filter	20	20
Bench-Scale sediment Filter	0	30
Bench-Scale GAC Filter	50	40

5.4 Conclusions

This study investigated the ability of the GWI water purification system to remove spheres with a mean diameter of 5.7µm from water at pH of 7 and 8.5. These spheres were used as surrogates for pathogenic *Giardia* cysts and *Cryptosporidium* oocysts. Tests were conducted on a bench-scale sediment filter as well as the full-scale sediment filter used by GWI. Separate tests were conducted on a bench-scale version of the GAC filter to determine the propensity of the same spheres to adsorb to carbon grains. Filtration was tested for various pH values found in Haitian water.

For the bench-scale sediment filter, results show that immediate breakthrough for water at pH 7 was 100 percent and for water at pH 8.5 was approximately 80 percent. Due to concerns about scaling and unwrapping the sediment filter, tests were conducted on brand-new, GWI sediment filters. For these full-scale sediment filters, immediate breakthrough was near 50 percent for both pH tests. As more water was filtered, the concentration of spheres in the effluent quickly increased to 80 percent, staying at this level for the remainder of the test. Clearly, these results indicate that a significant fraction of (oo)cysts are likely to pass through the GWI sediment filter as well.

Neither *Giardia* cysts nor *Cryptosporidium* oocysts were used in this study. It can be inferred for the sediment filter that cysts (mean diameter of 10µm), being larger than the surrogates (mean diameter of 5.7µm), would be removed with greater efficiency than surrogates. It can also be assumed that oocysts (mean diameter of 4µm) would be removed with less efficiency than either the surrogates or *Giardia*. This might change as the filter is used and becomes clogged with debris. This would decrease the pore size of the filter, which would increase the removal efficiency of *Giardia* and *Cryptosporidium*. For clean-bed conditions however, it is clear from laboratory tests that the sediment filter does not filter particles greater than 5µm with 50 percent efficiency. The filter's ability to remove slightly smaller particles (like *Cryptosporidium parvum* oocysts) is also suspect.

For the scaled-down GAC filter, removal efficiency ($1-C_e/C_o$) was slightly higher for lower pH as expected although the difference was slight. Immediate breakthrough was near 40 percent for pH 7 and approximately 50 percent for pH 8.5.

The flow of the water through the bench-scale GAC filter was based on the flow through the full-size GWI system. This flow was determined to be too fast to allow the cysts to reach equilibrium between water and carbon. As the volume filtered through the bench-scale GAC increased, the effluent concentration increased relative to the influent concentration until the end of the trial at which point the effluent was 80 percent of the influent concentration. For the partitioning experiment run at a neutral pH (just as in the GAC trial), it was observed that given enough time to reach equilibrium, the surrogates would tend to flocculate to the carbon more than to the water. The theoretical analysis predicted a breakthrough of 92 percent. Initial breakthrough values for both trials compare reasonably well with expected values. Given the trend of increasing effluent concentration for both GAC trials, it is believed that experimental values would have approached theoretical values.

The fact that a significant fraction of influent spheres were not filtered by either the bench-scale or full-size sediment filters indicates the need to employ a filter with smaller pore spacing. The manufacturers of the 5-micron sediment filter offer a 1-micron sediment filter as well. If the 1-micron filter is purchased, it is suggested that the new filter be tested to ensure that it can remove particles with a diameter of 3μm.

6 Differential Study

The differential study had two objectives: (i) to quantify the health impact of the program by an epidemiology study that measured differential health impacts in intervention and non-intervention sample groups after adequately controlling for relevant sources of variance in the two populations and (ii) to measure the level of microbial contamination of existing water sources in the area, to contrast this with stored water quality in intervention and non-intervention households, and to detect trends that explained variance in stored water quality. Both elements of the study were combined to identify solutions that may improve program efficiency.

6.1 Health Impact Study

6.1.1 Objectives

The health impact study sought to analyze the following issues:

- Is there a statistically significant difference in the incidence of water-borne disease between the treatment group (families using filters) and control group (families without filters)?
- Are the treatment and control groups identical in all respects except for their use of filters? Stated differently, is there selection bias in the distribution of the filters?
- What is the variance in health outcomes within each group? How much of this variance is explained by socio-economic, environmental and behavioural factors? How much is due to filter use?

6.1.2 Survey Design

Treatment and control groups in an epidemiology study should ideally be either (i) homogeneous in all aspects except in their coverage by the specific intervention being investigated or (ii) identically heterogeneous in all aspects. Researchers often randomize the distribution of the intervention to avoid problems caused by differences in population characteristics. This survey is different in that it is an observational study and not a randomized one. In other words, the survey examined the program as it existed in Dumay rather than through creation of a laboratory-like situation. It was therefore necessary to gather data on a vector of socio-economic and behavioural data that was likely to have an impact on the health outcome being studied. A failure to control for variance in these related factors would possibly bias the results, either giving too little or too much weight to the filter in explaining differential health outcomes between the groups. Apart from its non-interventional nature, an observational study has the advantage of quantifying the impact and interaction of other variables on the outcome being investigated. This information can in itself be vital to understanding the impact of the treatment.

6.1.3 Sampling Methodology

A total of 120 families were surveyed in Dumay, 62 of whom used the GWI filter and 58 of whom were not covered by the program. The sample that used the filter is referred to as intervention households while the non-filter owning families are termed non-intervention households. Families covered by the program were randomly selected from GWI's program records. Each circuit, corresponding to a village unit, was sampled in proportion to its representation in GWI's program. Lack of access to census or land records prevented perfect randomization of the non-intervention group.

6.1.4 Survey Implementation

Each family was administered a survey that solicited information on the health of each family member in the past month, particularly diarrheal incidence. The respondent was asked to provide health information on each family member. The respondent was in most cases the mother or grandmother of the family. In addition to health information, the respondent was polled for socio-economic data, described below.

6.1.5 Information Gathered

The survey gathered information on the following variables and groups of variables:

1. Health Outcomes: (i) A binary variable for whether or not each member of the family had experienced diarrhea (defined as three or more loose stools in a 24-hour period) in the past month. (ii) A binary variable for whether or not each member of the family had experienced fever (as defined by the respondent) in the past month.
2. Filter: a binary variable for whether or not the family owned a filter.
3. Geographic Location: A category variable for the circuit number assigned by GWI to each area, which roughly corresponded to a village unit.
4. Household Size: A continuous variable for the number of persons living in the surveyed house.
5. Source of Water: A category variable for source of water. Most families used one of two main sources. (i) Piped spring water capped at the source of springs in the surrounding hills and available at common village taps. (ii) Hand-pumped tube wells constructed by charities.
6. Sanitation Facilities: A category variable that measured whether a family used (i) a private bathroom (ii) a common bathroom or (iii) no sanitation facilities.
7. Quality of Housing: A category variable that classified houses as : (i) Earthern walls and floor, corrugated iron roof (ii) Earthen walls, cement floor, corrugated iron roof (iii) Cement walls, floor and roof, unpainted, unfinished fittings (iv) Cement walls, floor and roof; partially finished fittings (v) Completed concrete structure with modern fittings.
8. Rooms: A continuous variable for the number of rooms in the house
9. Electricity: A category variable for (i) No electricity (ii) Illegal Connections (iii) Legal Connection (iv) Generator

10. Age: A continuous variable for the age of each family member in years.
11. Education: A continuous variable for the educational attainment of each family member
12. Occupation: A category variable for the occupation of each family member recorded as (i) Share-cropping (ii) Cultivation of own land with hired labour (iii) Agricultural labour (iv) combination of share-cropping and agricultural labour (v) Services (Mason, Driver, Mechanic, Pastor, Bicycle Mechanic, Cook, Teacher) (vi) Factory Worker (vii) Vendor (viii) Commercial Enterprise (ix) Transfer from Family Member (x) Professional Service (Lawyer, Nurse)
13. Religion: A category variable recorded as (i) Catholic (ii) Protestant (iii) Voodoo (iv) no reported religion.
14. Family Assets: A number of continuous variables for the number of assets such as cows, goats, chickens, pigs, donkeys, sheep, horses, ducks, cars, TVs, radios and luxury appliances.
15. Behavioural Characteristics: A number of category variables for information on use of soap, diapers and hand-washing habits.
16. Use of other water treatment systems: a category variable recorded as (i) Add chlorine (ii) Borrow filtered water from friends when sick (iii) Boil water when sick (v) Boil water always
17. Filter use characteristics: Continuous variables for the date of last cleaning, year installed, rate of use
18. Reason no filter: A category variable for the reason families did not own filters.
19. Household hygiene: An observational measure of hygiene on a scale from 1 to 5.

6.1.6 Composite Indicators Generated

Some of the survey variables were then compressed into the following composite variables:

1. Composite Wealth Variable: Family assets were multiplied with average asset values to generate a cumulative asset value of visible family assets for each family. This variable is incomplete as a measure of family wealth as it omits assets such as bank accounts and expatriate incomes from family members in the United States. This variable was combined with the quality of housing variable to produce a categorical measure of relative wealth ranging from 1 to 5, weighting quality of housing by 75% and the cumulative asset value variable by 25%. A higher weight was accorded to the quality of housing variable, as health outcomes are more likely to be influenced by investments in housing than in the other non-visible assets that might have been missed in the cumulative asset value variable.
2. Composite Hygiene Variable: The observational hygiene variable was combined with the see-soap variable, which measured whether the household had soap. A higher weight was placed on the observational hygiene variable since the absence of soap might have indicated a temporary unavailability.
3. Family Educational Deficit: In considering the impact of educational attainment on health outcomes, the average family education deficit was considered a more relevant explanatory variable than an individual's education level. This captures

the impact of parental educational levels on family health outcomes. Each individual's deficit was worked out as the difference between the educational level the individual should have attained for her age with no breaks in the education process and the individual's actual attained level. The optimal level for an adult was defined as a university degree.

4. Adult Education Deficit: Since children contribute little to the educational deficit, families with high numbers of children register a low average family educational deficit. The adult education deficit improves on the average family measure by considering only the average of the education deficit of persons above 15 years of age. This would include members of the family involved in household tasks such as cooking, cleaning and looking after children and other activities in which educational attainment can be expected to improve hygiene practices relevant to health outcomes.

6.1.7 Key Results

- Of the total sample of 841 individuals, 86 (10.23%) were reported to have experienced at least one episode of diarrhea in the month preceding the survey.
- Of the 380 individuals with no access to a filter at home, 56 (14.74%) were reported to have experienced diarrhea.
- Of the 461 individuals with access to a filter at home, only 30 (6.51%) were reported to have experienced diarrhea.
- This suggests that the population with access to a filter experienced an 8.23 percentage point lower incidence of diarrhea than the population with filters.
- Intervention and non-intervention populations could not be considered identical. Intervention households had a higher average quality of housing, better sanitation facilities and lower education deficit than non-intervention households.
- After controlling for differences in socio-economic factors and hygiene, the filter was associated with a 5.2 percentage point lower probability of diarrhea. The result is statistically significant but indicates a lesser impact than earlier calculated.
- Improved sanitation facilities were associated with lower diarrheal incidence.
- Improved quality of housing was associated with lower diarrheal incidence, but the result was not statistically significant at 95% confidence.
- Better hygiene was associated with lower diarrheal incidence, but the result was not statistically significant at 95% confidence.
- Age was strongly correlated with diarrheal incidence, with younger and older persons more at risk.
- For children of age 5 and under, the filter was associated with a lower diarrheal probability of 16 percentage points, controlling for all other factors. The average incidence of diarrhea in the group was 31.16%.
- For older children in the 6-16 age group, the filter was associated with a lower diarrheal probability of 4 percentage points, controlling for all other factors. The result was not significant at 95% confidence.

- For persons of age 16 and older, the filter was associated with a 4 percentage point lower probability of diarrhea, controlling for all other factors. The result was not significant at 95% confidence.
- Of the 369 individuals who used piped spring water, 11.38% experienced a diarrheal episode.
- Of the 332 individuals who used well water, only 7.23% experienced a diarrheal episode.
- Amongst the population who used piped spring water, the filter was associated with a 7.7 percentage point lower incidence of diarrhea.
- Amongst the population who used well water, the impact of the filter was not significant in explaining diarrheal incidence.

6.2 Water Quality Impact Study

6.2.1 Objective

Previous studies undertaken for GWI have used presence-or-absence testing to determine microbial contamination in community water sources and domestic stored water in Dumay. While a useful indicator of microbial contamination, presence-or-absence testing provides no information on the relative levels of contamination in source water. This study sought to quantify the level of microbial contamination in different community water sources and domestic stored water by using membrane filtration to measure the levels of the microbial indicator organisms total coliform and escherichia coli.

6.2.2 Water Quality Testing Method

The membrane filtration method involves filtering a measured volume of sample, or an appropriate dilution of it, through a membrane filter, which has a pore size of 0.45 microns and is usually made of cellulose esters. Micro-organisms are retained on the filter surface which is then incubated face upwards on a suitable selective medium containing lactose. White absorbent pads are used to absorb the liquid media in the petri dish. Characteristic acid or aldehyde producing colonies develop on the membrane and these are counted as either presumptive coliform organisms or faecal coliform organisms depending on the incubation temperature. The visible colonies are counted and expressed in terms of the number present in 100 ml of original sample. Samples were collected in Whirl-Pak bags and transported in a cooler fitted with an ice-pak. The samples were filtered within four hours of collection.

6.2.3 Sampling Methodology

A total of 25 community water sources were tested in duplicate. These included 22 wells and 3 piped spring sources. The sampling covered 16 out of 22 circuits.

Amongst the 58 families with no filters, tests of stored household water quality were conducted on 47 families. One family drank directly from source, two families did not have water stored in the house at the time of the survey and eight families' water could not be tested for logistic reasons.

Amongst the 62 families with filters, tests of filtered water quality were performed on 34 families. Nine families did not have water in their filter at the time of the survey, one family had a dysfunctional filter, and no tests were performed on 17 families whose water had adequate chlorine residuals.

6.2.4 Results

6.2.4.1 Source Water Tests

The following table summarises the results of the source water quality tests:

Circuit	Source	TC (1)	TC (2)	EC (1)	EC (2)
1A	S	240	240	1	2
3A	W	2	0	0	0
3B	W1	1	0	0	0
3B	W2	0	2	0	0
4B	W1	8	22	3	3
4B	W2	2	2	0	0
5A	W	0	0	0	0
5B	W	0	0	0	0
6A	S	232	240	9	9
6B	W1	3	0	0	0
6B	W2	7	4	0	0
6B	S	168	164	0	0
8A	W1	6	7	0	0
8A	W2	2	2	0	0
8B	W1	0	0	0	0
8B	W2	0	0	0	0
9B	W1	0	1	0	0
9B	W2	0	0	0	0
9B	W3	11	1	0	0
10A	W1	0	0	0	0
10A	W2	0	0	0	0
10B	W1	4	10	0	0
10B	W2	10	4	0	0
11A	W	0	2	1	2
11B	W	2	4	1	1

* TC = Total Coliform
* EC = E-Coli
* S = Piped Spring Water
* W = Well Water

- The total coliform count in well water was found to be 122 cfu in 46 samples for an average of 2.65 cfu/100ml.
- The total e-coli count in well water was found to be 13 cfu in 46 samples for an average of 0.28 cfu/100ml.
- The total coliform count in piped spring water was found to be 1,284 cfu in 6 samples for an average of 214 cfu/100ml.
- The total e-coli count in piped spring water was found to be 21 cfu in 6 samples for an average of 3.5 cfu/100ml.

The inability to sample more piped spring water taps in the village is a weakness in the study. Other MIT groups testing raw water at other taps found contamination of the same order of magnitude suggesting that the results were representative.

6.2.4.2 Stored Water Tests On Non-Intervention Households

- The average total coliform content in 41 households was 2,545 cfu/100ml, with a standard deviation of 1,851.
- The average total coliform content in 19 households that drew piped spring water was 2,977 cfu/100ml , with a standard deviation of 1,879.
- The average total coliform content in 20 households that drew water from wells was 2,324 cfu/100ml, with a standard deviation of 1,804.
- An OLS regression showed that mean total coliform levels in stored water in non-intervention households decreased with better sanitation and better quality housing; it increased with adult education deficit and household size. None of the coefficients was statistically significant.
- The average e coli content in 45 households was 162 cfu/100ml, with a standard deviation of 514.
- The average e coli content in 19 households that drew piped spring water was 232.5 cfu/100ml, with a standard deviation of 751.
- The average e coli content in 20 households that drew water from wells was 110 cfu/100ml, with a standard deviation of 242.
- An OLS regression showed that mean e-coli levels in stored water in non-intervention households decreased with better sanitation and increased with adult education deficit, household size and better quality housing. The sanitation variable was significant at 93% confidence. None of the coefficients was statistically significant.

6.2.4.3 Stored Water Quality in Intervention Households

- In 11 filter-owning households with adequate residual levels of chlorine in both buckets, there was little evidence of microbial contamination, with average TC= 0.68 cfu/100ml and average EC=0.05 cfu/100ml.
- In 10 filter-owning households with adequate residual levels of chlorine in the top bucket but inadequate chlorine in the bottom bucket, there was little evidence of

microbial contamination, with average TC= 2.25 cfu/100ml and average EC=0.1 cfu/100ml.

- In 1 filter-owning households with inadequate residual levels of chlorine in the top bucket but adequate chlorine in the bottom bucket, there was little evidence of microbial contamination, with average TC= 10.5 cfu/100ml and average EC=0.
- In 10 filter-owning households with inadequate residual levels of chlorine in both buckets, there was substantial evidence of microbial contamination, with average TC=913 cfu/100ml and average EC=22.3 cfu/100ml. (This result must be interpreted with caution as it is influenced by outliers).

6.3 Discussion

The differential study investigated the impact of a point-of-use water treatment system in a rural area of Haiti. Many results of this study corroborated intuitive expectations and the findings of previous literature on point-of-use water treatment systems. The results also pointed to opportunities for GWI to improve program design and efficiency.

The study found that the intervention population had a lower incidence of diarrhea than the non-intervention population. Although part of this effect should be attributed to better housing and sanitation facilities, the filter itself was independently associated with a 50% lower incidence of diarrhea at 95% confidence. While this is a substantial impact, it bears mentioning that this effect was on a relatively low base incidence of diarrhea of around 11%. The greatest impact of the filter was felt in two populations: the under-6 age group, in which the filter was associated with a 16 percentage lower probability of diarrhea, and the population that used piped spring water. The impact of the filter on older populations was of a lower magnitude and was not statistically significant. The filter was not significantly associated with diarrheal incidence in the population that drew water from wells. Diarrheal incidence was not correlated with an individual's sex.

Source water quality analysis supported the findings of the health impact study. Water from wells was found to be largely free of faecal contamination. Piped spring water was more contaminated in comparison. Importantly, stored water in non-intervention houses was considerably more contaminated than source water, suggesting post-collection contamination is a major concern.

Further investigation of water quality and health trends at different times of the year may provide the basis for effective program restructuring. If well water is found to be of acceptable quality throughout the year (measured in terms of microbial contamination as well as indicators of potability such as salinity and turbidity), GWI may consider encouraging the use of wells over piped spring water in Dumay. This may require an investigation of groundwater reserves followed by the development of a few new wells in areas currently served only by spring water. Access to pure water sources would need to be supplemented by interventions that promote the use of safe storage containers and behavioural change on the lines of the CDC's safe water system. In other words, it may no longer be necessary to use the GWI's two-bucket cotton-and-carbon filter system if access to clean source water can be extended to the whole community. Instead, the community could be provided with, or encouraged to buy, two special plastic buckets with a tap and a recessed opening that prevents the entry of hands or other containers. The stored water may need to be dosed with a limited amount of bleach to prevent bacterial regrowth. This approach has the advantage of being cheaper and therefore more easily extended to the wider community. It will also reduce the intervention community's exposure to potentially dangerous tri-halo methanes and other disinfection by-products.

This study examined only one village. It may not be possible to provide access to clean water in all the areas that GWI works in, owing to financial constraints and/or unavailability of clean sources. GWI's current point-of-use filtration system is probably a good intervention where clean water sources are unavailable. However, even in such communities, there is a strong case for introducing safe storage and disinfection interventions to households that are yet to be provided with a filter.

Clearly, such program modifications would require considerable research into economic feasibility, resource availability, organizational challenges, and project sustainability. This study does not dwell on these issues; it merely draws attention to evidence that a point-of-use water treatment intervention based on safe storage, minimal disinfection and behavioural change may be a cost-effective means of extending program reach in areas with access to relatively safe source water such as Dumay.

7 Conclusion

For the SODIS project, the fully painted bottle regimes were not significantly more effective for reaching the required temperatures than the half painted bottles. For further studies, bottles should only be half painted in order to also allow for synergistic effects with UV. It is recommended that future studies also evaluate the effective use of solar reflectors/reflective bottle backing with the clear and half painted bottle regimes in non-tropical climates.

The primary recommendation of the chlorine demand study is that Gift of Water, Inc. implement mixing in the top bucket. This could be achieved in one of two ways. One solution is to create a small paddle, which would be used to stir like a spoon, and would be sold with the filtration system. Another possible solution is to require the use of a third bucket. Bleach should be placed in the Gift of Water, Inc. top bucket prior to pouring the water from the third bucket into the top bucket. The momentum of the water falling onto the bottom of the bucket should be sufficient to mix the bleach. A future study is recommended in order to achieve the initial goal of this study, reducing the amount of chlorine used in the Gift of Water, Inc. filter.

The microbiological study demonstrated the failure of the GWI filters to consistently remove *Giardia lamblia* and *Cryptosporidium parvum* from simulated Haitian water. It is recommended that GWI replace the 5-micron polypropylene filters with 1-micron polypropylene filters. Further testing should be completed on the new filters to ensure (oo)cyst removal.

The differential study found that ownership of the filter was correlated with a five percentage point lower incidence of diarrhea, controlling for income, education, quality of housing, sanitation facilities, sex and age. Water quality analysis using membrane filtration revealed that post-collection contamination is the largest source of microbial contamination in household water. These findings indicate that the GWI program has been effective in lowering the risk of diarrhea amongst families with filters.

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