# Filtration of *Giardia* cysts from Haitian Drinking Water

By

Michael Joseph Borucke

S.B. Civil and Environmental Engineering
Massachusetts Institute of Technology, 2001

Submitted to the Department of Civil and Environmental Engineering
In Partial fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING
In Civil and Environmental Engineering
At the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE 2002



Signature of Author_____
Department of Civil and Environmental Engineering
May 15, 2002

Certified by_____
Dr. Philip M. Gschwend
Thesis Advisor
Ford Professor of Engineering in Civil and Environmental Engineering

Certified By_____
Daniele Lantagne
Thesis Advisor
Lecturer in Civil and Environmental Engineering

Accepted by_____
Oral Buyukozturk
Chairman, Departmental Committee on Graduate Studies

# Filtration of *Giardia* cysts from Haitian Drinking Water

By

Michael Joseph Borucke

Submitted to the Department of Civil and Environmental Engineering
On May 24, 2002 in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering in
Civil and Environmental Engineering
June 2002

## Abstract

*Giardia lamblia* and *Cryptosporidium parvum* are parasitic protozoa that exist in the environment as a cyst and oocyst, respectively. Their ubiquity in waters around the world, coupled with their resistance to chlorination, make *Giardia* and *Cryptosporidium* two of the most significant waterborne pathogens. Their impact on human health is especially pronounced for people in developing nations such as Haiti. This study investigated the effectiveness of the Gift of Water, Incorporated (GWI) filtration system in removing *Giardia* cysts and *Cryptosporidium* oocysts from water. The GWI sediment filter as well as bench-scale mock-ups of the granular activated carbon filter and sediment filters were tested by filtering water spiked with surrogates through each filter separately. The surrogates were fluorescent microspheres of a size between that of *Giardia* cysts and Cryptosporidium oocysts. Microspheres were detected in effluent water using a spectrofluorimeter; tests were run at pH values representative of those observed in Haitian water.

The bench-scale sediment filter removal efficiency for surrogates was approximately 30 percent and 0 percent for pH values 8.5 and 7, respectively. The full-scale sediment filter removed 20 percent of surrogates for both pH 7 and 8.5. The bench-scale granular activated carbon filter removed 50 and 40 percent for pH of 7 and 8.5, respectively. These results suggest that GWI should consider switching to sediment filters with smaller pore spacing to ensure protozoan (oo)cysts are removed.

Thesis Supervisor: Philip M. Gschwend
Title: Professor of Civil and Environmental Engineering

## Acknowledgments

I'd like to thank the following persons for helping me in various ways to get this thing done: Phil Gschwend, Daniele Lantagne, Phil Warwick, Matt Cyr, Wanda, Nathan & Tutu, and all the people in Haiti who helped with my project, especially the children who helped carry our buckets up the mountain. Thanks to my fellow travelers: Arun Varghese, Sara Jo Elice, and Julie Parsons. Gracias to all my MEng people, Amy Marie Accardi-Dey, John McFarlane, the custodian who encouraged me more than anyone, Eric Adams, my SJC/Thistle/R&R comrades, Bob Marley, Ani DiFranco, The Clash, Fifteen, Tosci's people and their coffee, and my friends without whom, I'd be lost.

# Table of Contents

# List of Tables

# List of Figures

# 1 Introduction

In 1995, the vice president of the World Bank said, "the wars of the next century will be fought over water" (Shiva, 2002). The statement underscores the water crisis affecting a significant portion of the world. By 1996, 1 in 4 of the world's people were without access to safe drinking water (World Bank, 2000a). The World Water Forum has predicted that by 2025, the fraction will increase to 1 in 3 people worldwide (Common Dreams, 2002).

Since 1970, the global per capita water supply has declined by 33 percent (Shiva, 2002). Reasons for the current global water crisis are varied and complex, and include mismanagement of water resources, overpopulation, environmental degradation, and regional and ethnic conflict. Overpopulation alone does not account for global water scarcity: The rate of water withdrawal has exceeded of population growth by a factor of two and a half.

When the available drinking water per person is less than 1,000 cubic meters per year in a given country, that country is considered to be water-stressed (Shiva, 2002). In 1998, 28 countries experienced water stress or water scarcity. Predictions estimate that the number will increase to 56 by 2025.

Sustainable solutions to the water scarcity problem have proven difficult to come by for the international financial institutions (IFI) (Shiva, 2002). IFI's such as the World Bank have funded several large-scale developmental water projects, some with deleterious results. Even NGO's with the best of intentions have promoted solutions that have ended up harming more than helping. Reliance on tube wells and other modern technologies has, in many cases, promoted the intensified extraction of water, which has tended to deplete aquifers more quickly. This in turn has increased infiltration of contaminants such as salt and arsenic. The top-down paradigm of solutions to water scarcity problems in the developing world has led to the observation that, "when development philosophy erodes community control and instead promotes technologies that violate the water cycle, scarcity is inevitable."

One of the prevailing mechanisms with which to handle water issues in developing nations has been privatization (Shiva, 2002). This approach involves relegating management of water to the private sector, and allowing the distribution of water to be determined solely by market forces. Of the 40 loans provided by the International Monetary Fund to the developing countries in 2000, 12 required the full or partial privatization of the country's water supply as a condition for loan approval. The World Bank, with USD20 billion in commitments for water projects globally, also promotes privatization. As is often the case, it is corporations and even consortiums of corporations that procure contracts for these projects, not the states themselves.

In countries where water privatization has occurred, countries such as Chile, Britain, South Africa, and Ghana, the results of private sector management have been less than

promising (Shiva, 2002). Prices for drinking water and sanitation services have increased, while accountability to customers has not improved in the deregulated market.

Today less than forty percent of the Haitian population has access to safe drinking water (World Bank, 2002a). Attempts to improve people's access to water in Haiti follow in the same pattern as seen on a global level.

Although the privatization of water has yet to be realized in Haiti, reports from the World Bank suggest that failures of past water-related projects in Haiti could have been successes if the projects had been privately managed (World Bank, 2002a). In addition the Bank has pushed several times for the privatization of Haitian utilities since the mid-eighties. Only resistance from the Haitian government has impeded efforts to this end (Farmer and Bertrand, 2000). The recent suspension of international loans to Haiti has put World Bank funding on hold.

Still the search for an appropriate and sustainable scheme to provide safe water to the general population continues. The filter system manufactured by Gift of Water, Inc., (GWI) is one proposed method. The system is designed for single-family use and consists of a sediment filter and carbon filter combined with chorine disinfection. Four graduate students from the Massachusetts Institute of Technology (MIT) traveled to Haiti in January 2002. Three of these students investigated the effectiveness of the filtration system through an epidemiological survey, a chemical study, and a biological study.

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, Holly Hills, Fl) 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.

# 2 Haiti

## 2.1 Potable Water in Haiti

Less than half of all Haitian people have access to safe drinking water (Garratt, 2002). The reasons for this dismal fact have historical roots reaching back centuries. Today, the geo-political turmoil, the socio-economic stagnation, and the environmental degradation of Haiti have all directly and indirectly affected the ability of the population to secure clean water (Fig. 2-1).


**Figure 2-1: Political Map of Haiti (University of Texas Library, 1999)**

### 2.1.1 Development Assistance

The largest foreign donor to Haiti is the United States, which lends to Haiti through the US Agency for International Development (USAID). Development assistance to Haiti from USAID dropped to nil in 2000 following the presidential elections and has remained at that level up through FY2002 (USAID, 2002). The US has chosen to send funds to Haiti through an Economic Support Fund (ESF) instead. ESFs were established by Congress to "promote economic and political stability in strategically important regions where the United States has special security interests" (USFMA, 2002) In the past 4 years, the US has given Haiti approximately $75 million in aid; 2/3 of which came through ESF programs.

### 2.1.2 Lack of Infrastructure

Given the directed nature of a significant portion of past foreign aid, Haiti has had few resources with which to provide infrastructure capable of supporting its population (Garratt, 2002). There is no public sewage system in Haiti; the wastewater treatment facilities are too few and too ill equipped to address waste remediation on a nation-wide scale. In Port-au-Prince, nearly all of the sources supplying the city with water are polluted or threatened with pollution because of overpopulation. The city was designed for 200,000, but has a population of 2 million, incorrect disposal practices, and zero waste infrastructure.

### 2.1.3 Environment

A recent study conducted by the Center for International Earth Science Information Network (CIESIN) ranks the world's countries according to an environmental sustainability measures (CIESIN, 2002). On the environmental sustainability index, Haiti ranks 137$^{th}$ out of 142 countries. The two most significant environmental problems currently in Haiti are biodiversity and basic human sustenance. The former has a significant correlation to the loss of Haitian forests. Most of the deforestation took place in the nineteenth century so that only 8 to 9 percent of Haitian forests remained by the time Duvalier took power in 1954. More than 98 percent of Haiti is now deforested (World Bank, 2002a). As peasants cut the remaining trees to produce charcoal to sell for income, desertification occurs, which can affect local climate change. Forest loss also contributes to soil erosion since tree roots no longer hold the soil. Each year 20,000 tons of topsoil washes into the ocean (PAHO, 2001).

## 2.2 Mortality and Intestinal Infection

The difficulties in securing potable water that arise as a result of the above in turn are responsible for significant health impacts on the population in Haiti (PAHO, 2001). Intestinal diseases, such as those caused by microorganisms in drinking water are the leading cause of illness and death-12% of mortality cases-in children under 5 years of age. (Such diseases account for 12% of the child mortality cases worldwide). The infant mortality rate was 80 reported deaths for every 1,000 births in 2000. In the one-to-five year-old category, the mortality rate in 2000 was 101.1 reported deaths for every 1,000 births.

## 2.3 Morbidity and Intestinal Infection

Intestinal infections accounted for 5% of the hospitalization cases in children 0-14 years old in 1995 (PAHO, 2001). The proportion afflicted and the severity of affliction increases in younger children. The incidence of diarrhea in children 6-11 months old is 47.7%. Diarrhea is often associated with acute respiratory infections and malnutrition.

It is therefore of vital importance to identify and address the most significant causes of diarrhea in developing nations.

# 3 Protozoa

There exist many microorganisms in drinking water, and many of these are pathogenic to humans (WHO, 1993). Two microbial species of import to this study are both protozoa: *Giardia lamblia* and *Cryptosporidium parvum*. Both are present in water throughout the world, and both are parasites that exist as dormant spores outside of a host. Both are highly resistant to traditional chlorination methods.

## 3.1 *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.

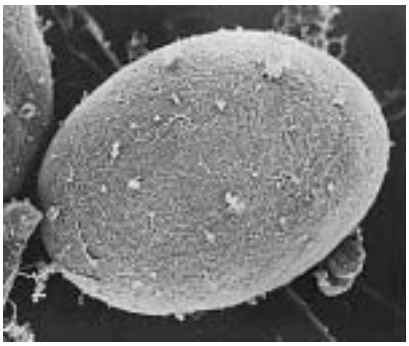

**Figure 3-1: Field Emission Microscope scan of *Giardia* cyst (University of Minnesota, 2001)**

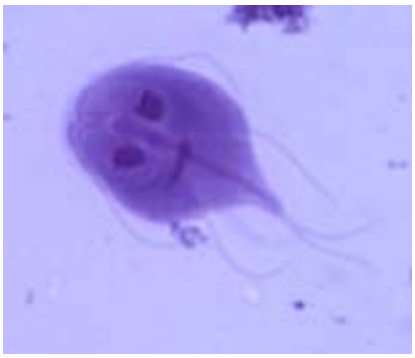

**Figure 3-2: *Giardia*: trophozoite stage (National Institutes of Health, 1998)**

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. 3-1). 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. 3-2). 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.

## 3.2 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.

## 3.3 *Giardia* Species and Hosts

Currently, there are currently 40 known species in the *Giardia* genus (Campbell, 2002). Three prevalent species are *Giardia lamblia*, *Giardia muris*, and *Giardia agilis*. The first species has been found in humans and mammals; the second species has been identified in rodents, birds and reptiles; and the last species has been found in amphibians (Taylor, 1995).

While in Haiti, it was observed at some potable water sources that mammals such as burros would be in the vicinity of the water source. Their presence at the water source was necessary to carry the water in plastic canisters on their backs, but they also constitute a real risk for *Giardia* contamination. At other locations, livestock including different fowl species were able to root around near the faucet of the cistern.

## 3.4 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.

Several studies investigated whether there is a correlation between seasonal variation and the prevalence of gastrointestinal infections. Findings suggest that if correlations do

exist, they are region-dependent. Amahmid et al. (2001) observed a seasonal correlation to *Giardia* concentrations in wastewater from a stabilization pilot plant in Marrakech, Morocco. Minimum concentrations occurred in the late fall and winter while maximum concentrations occurred in spring and summer. Perch et al. (2001) did not find a correlation between *Giardia* concentration and seasonal variability in stool samples taken from young children in Guinea-Bissau. Seasonal correlation was found, however, with *Cryptosporidium* concentrations, peaking just before the rainy season in spring. In one Nigerian community, Nzeako (1992) found that infections of protozoan parasites began at the start of the rainy season in April. In another region of Nigeria, the Ibadan population had high incidence of intestinal infection caused by protozoa during the dry months caused by reliance on contaminated water sources Ogunba (1997). In Sao Paolo, Brazil, Torres et al. (1999) observed that seasonal patterns of *Giardia* infection could change from year to year. In northern Haiti, the rainy season runs from October to May, while in the South it is the reverse-May to October. Research in each of these regions might be done to determine if a correlation exists between *Giardia* infection and the seasons. Most likely the population already knows if incidents of sickness increase with the change of season.

## 3.5 *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 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.

Sources of contamination in Milwaukee included heavy rainfalls before the epidemic (Addiss et al., 1995). These events could have washed organic matter including wastes from a nearby slaughterhouse into the source lake, or could have caused combined sewage overflows, allowing wastes into the source lake. Asymptomatic infection is also apparent in *Cryptosporidium* infection. Of the 35 infants that tested positive for *Cryptosporidium* after the epidemic, 29 percent did not have diarrhea in their stool samples.

*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.

## 3.6 Protists in Haiti

There has been little investigation into the presence of (oo)cysts in Haiti. However, two reports have found evidence of *Giardia* and *Cryptosporidium* in stool samples of Haitian people. 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.

## 3.7 *Risk Assessment*

The concentration of *Giardia* in water bodies is often very low. Bella and Tam (1998) found *Giardia* in concentrations as high as 468 cysts per liter downstream of treated effluent discharges in Hong Kong. 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. USEPA regulations require a maximum allowable concentration of zero (oo)cysts per liter (USEPA, 1998). Similarly, 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. This study investigates whether the GWI filter meets the standards from protozoan removal.

# 4 Gift of Water, Inc.

## 4.1 Filtration System

The Gift of Water, Inc. (GWI) Purifier system consists of two identical 19 liter buckets stacked one on top of the other (Fig. 4-1). In practice, 5mL of chlorine is added to 5 gallons of raw water in the top bucket and is allowed to sit for roughly 30 minutes.

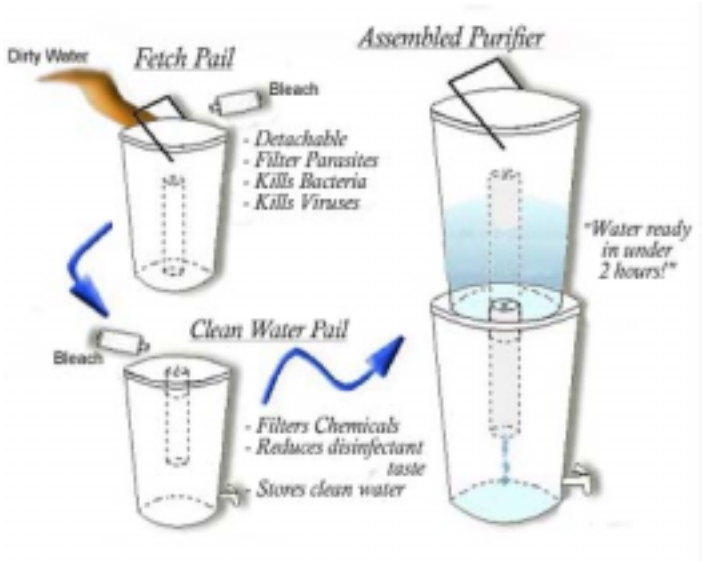


**Figure 4-1: Filtration and Disinfection Processes in the Gift of Water filtration system (Gift of Water, Inc. website)**

A residual chlorine amount of five drops of bleach is added to the bottom bucket for safety. Eagle Spring Filtration located in Holly Hills, Florida, manufactures both filters.

The sediment filter in the top bucket consists of a polypropylene string approximately 150 meters in length wound around a plastic tube open at both ends. Along the side of the tube, there are perforated squares, each with an area of 1.6cm$^2$ (Lantagne, 2001). The tube itself has a diameter of 3.5cm; when wound with the polypropylene string, the diameter increases to 5.7cm. The length of the filter is 24.8cm.

### 4.1.1 Disinfection with Chlorine

Current filtration practices for the GWI purifier rely on chlorine for disinfection of microorganisms in the water. While chlorination at current levels is sufficient to disinfect bacteria, there is reason to believe that these levels may be insufficient to disinfect *Giardia* cysts (Vressman and Hammer, 1993).

The Ct value is often used as a convenient measure of disinfection for microorganisms. It is the product of the concentration of free chlorine residual and the time that that

concentration contacts microorganisms in the water. The Ct value is calculated as a function of pH and temperature of the water.

For water at a temperature of 5°C and a pH range of 6-7, Vressman and Hammer (1993) suggests a Ct value range of 65-150mg*min/L for a 99 percent inactivation of *Giardia* cysts. In contrast, the Ct value for a 99 percent inactivation of *Escherichia coli* at the same temperature and pH was 0.045mg*min/L. It is therefore necessary to determine to what degree chlorination can deactivate cysts.

One estimate for the free residual chlorine concentration of the GWI system under current practice is 6.5$mg_{Cl}$/L or 6.5ppm. The current procedure requires that the chlorinated water stand for 30 minutes before filtering. Multiplying this time by 6.5mg/L gives a Ct value for this concentration is 195mg*min/L. This is greater than most Ct values needed for a 99.99 percent removal of cysts for Haitian water, but this number assumes there is no chlorine demand. Quantification of chlorine demand in Haitian water is not well known however. The fact that there is chlorine demand indicates that the actual free residual chlorine will be less than 6.5mg/L. A conservative estimate of the free residual chlorine concentration after chlorine demand would be 20 percent of the possible residual or 1.3ppm.

Vressman and Hammer (1993) provide an empirically derived equation for Ct values:

$$Ct = 0.985 * C^{0.176} * pH^{2.75} * T^{-0.147} \quad (4.1)$$

where C is the free chlorine concentration (mg/L) after disinfection, and T is the temperature (°C). The Ct values necessary for a 4-log (99.99%) removal of *Giardia* at various locations in Haiti were calculated using equation (4.1) and a 1.3ppm for the free chlorine residual. Ct values averaged 164mg*min/L (Table 4-1).

**Table 4-1: Ct values needed for a 4log disinfection given pH, Temperature, and free chlorine concentration at various locations**

| Location | Type/Name | pH | Temperature C | Ct values (mg*min/L) C = 1.3mg/L | Date |
|---|---|---|---|---|---|
| Dumay | Captage | 7.2 | 26 | 145.5 | 1.15 |
| Fon-Veret | Cistern | 7.8 | 21 | 187.2 | 1.16 |
| Karetye | Surface Water | 8.2 | 16 | 223.6 | 1.17 |
| Barasa | Spring | 7.7 | 18 | 184.8 | 1.18 |
| Ba Limbe | Spring | 7.2 | 27 | 144.7 | 1.20 |
| Ba Limbe | Captage | 7.6 | 25 | 169.9 | 1.21 |
| Characol | Basaline | 7.6 | 28 | 167.1 | 1.22 |
| Les Palmes | Tewouj Captage | 7.3 | 20 | 157.1 | 1.24 |
| Les Palmes | Senak Spring | 7.4 | 24 | 158.8 | 1.25 |
| Les Palmes | Cistern | 7.1 | 20 | 145.6 | 1.26 |
| Dumay | Captage | 7.3 | 26 | 151.2 | 1.27 |
| Dumay | Captage | 7.5 | 25 | 163.8 | 1.27 |
| Dumay | Well | 7.3 | 26.5 | 150.8 | 1.28 |
| Dumay | Captage | 7.3 | 25.5 | 151.6 | 1.29 |

Free residual chlorine concentration of 1.3ppm gives a Ct value of 1.3mg/L * 30min = 39mg*min/L. Using the average Ct value of 164mg*min/L (Table 4-1) as a 99.99 percent removal, the Ct value of 39mg*min/L would lead to

$$(39\text{mg*min/L}) * (4\text{log}) / (164\text{mg*min/L}) = 0.95\text{log} \quad (4.2)$$

a 0.95log removal, or 89 percent removal efficiency. With this rate of disinfection, it is of interest to determine whether the filters can remove the fraction of *Giardia* cysts that resist chlorination.

The standards for water quality according to WHO (1993) require zero concentration of *Giardia* and *Cryptosporidium*. In practice, calculations for a 99.99 percent removal can only be a guideline for *Giardia* disinfection; they cannot ensure every cyst will be removed. The sediment filter and GAC filter will necessarily be utilized to remove the remaining protozoan (oo)cysts.

### 4.1.2 Polypropylene String

The polypropylene string wound around the core has no charge (Dann, personal communication). 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 filtered by the such a filter.

### 4.1.3 Carbon Filter

The GAC filter consists of a segment of PVC tubing packed with 220grams of granular activated carbon. The filter has an opening at the top where the check valve is inserted as well as an opening on the bottom where a mesh screen approximately 1.5cm in diameter allows water to pass through while retaining the GAC grains. The filter is 21cm in length and 4.8cm in diameter.

The 12/40 bituminous carbon is coal-based and it is imported from several different countries by American Carbon, California (Turquand, personal communication). 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. Once imported, the carbon grains are placed in a kiln at the factory and heated in the absence of air to a temperature of 1000$^{o}$C. Oxidizing gases are passed through the heated carbon creating small fissures within the carbon grain itself. This process is known as activation, and it increases the surface area of the carbon used in the GWI filter to 1000m$^2$/g. The reasoning behind activating carbon is to increase the effective surface area for molecules to adsorb, which results in greater filtration removal (Fig. 4-2).

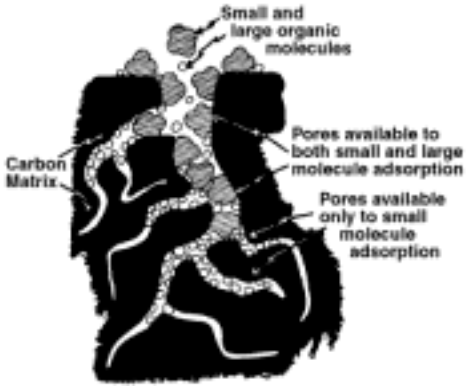


**Figure 4-2: Diagram of Activated Carbon Pore Space (Seelig et al. 1992)**

In order to utilize this extra area, molecules have to be small enough to enter the pore space. The mean pore radius, or pore size, of the activated carbon is in the range 2.5-5.0x$10^{-9}$m. This length-scale is three orders of magnitude smaller than the *Giardia* cysts (5x$10^{-6}$m); hence, the cysts are physically prevented from entering the pores. As the American Carbon brochure recognizes, the newly formed spaces are meant to adsorb molecules such as hydrogen sulfide and chlorine; molecules of a size close to that of the pore spaces (Turquand, personal communication). Though they are too large for the pore space, *Giardia* cysts can still flocculate to the exterior of the carbon grains.

## 4.2 Porosity of GAC

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.

## 4.3 Laboratory Setup

A bench-scale model of the GWI filter was used for laboratory testing (Fig. 4-3). 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, personal communication).

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, 2001). The carbon used came from GWI, so it is the same carbon used in Haiti filters.

**Figure 4-3: 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 Methods

## 5.1 Sampling for *Giardia* and *Cryptosporidium*

In Haiti, ten water samples were taken using the Pall-Gelman Life Sciences Envirochek filter. The filter has an effective area of 1300cm$^2$, a 1-micron pore size and a 70 percent recovery rating for target organisms. The sampling procedure used in Haiti was as follows. A rubber hose connected the water source to an Envirochek filter, which was connected to a peristaltic pump powered by a car battery (Fig. 5-1). Water was pumped from the source through the filter and the filtered water was subsequently discarded. The motor pumped water through the filter at an average rate of 0.020L/s. Every sample ran for approximately 1 hour giving a total volume filtered of approximately 70L. Since (oo)cyst concentration in the environment is typically low, a large filtered volume is necessary to increase the probability of cyst capture.

**Figure 5-1: Filtering Haitian Water: Generator pumps water from source through Gelman filter, and returns water to the source downstream of uptake**

The maximum holding period—time between sampling and detection—for Envirochek filter samples is 36 hours as specified by the manufacturer (Pall Corporation, 2002). The holding periods for samples in Haiti varied from 48 hours to 170 hours. The suggested temperature is between 0 and 4$^o$C. Although cysts were kept at prescribed temperatures, it is possible for cysts to have degraded in transit because of the large holding times.

### 5.1.1 Detecting *Giardia* and *Cryptosporidium*

Detecting *Giardia* or *Cryptosporidium* in the environment is nearly impossible with conventional techniques for bacterial detection. (Oo)cysts cannot reproduce outside a host, nor can they be grown on media used for bacterial cultures. This technical difficulty creates economic considerations, which are limiting to protozoan research. The

equipment needed for (oo)cyst detection is expensive and ill suited for work in the field. One popular method of detection is immunofluorescence staining in which fluorescent antibodies attach to cyst walls and are subsequently viewed and counted under a special fluorescence microscope (Iturriaga, 2001; Hu, 2002). The necessary laboratory equipment used for this method was not transferable to Haiti.

Another method for protozoan detection is polymerase chain-reaction (PCR) analysis (Jellison, 2002). This method involves extracting DNA from the sample and selecting for a characteristic length of chromosome by gel electrophoresis. Kristen Jellison used PCR analysis to detect *Cryptosporidium* in water samples brought back from Haiti. All of the ten samples tested negative for *Cryptosporidium* oocysts. The samples have yet to be tested for *Giardia* using PCR techniques. There was no positive control for either oocysts or cysts during sampling, transport and detection. Therefore, a negative result for (oo)cyst presence in the filters does not mean that viable (oo)cysts were not present in the filter when the sample was taken.

## 5.2 Suitability of the Bench-scale GAC filter

To determine whether the bench-scale GAC filter was an appropriate model for the full-scale GAC, removal efficiency changes with approach velocity, bed depth, and collector size were examined. The graphs presented in Elimelech et al. (1995) relate the above variables to removal efficiency (see below). For each graph, collision efficiency, $\alpha$, were assumed to be unity; in other words, it is assumed that every collision results in attachment-ideal conditions. This was not the case in the following study as chemical enhancement is not being used in the GWI filters. Also, the graphs assume clean-bed conditions throughout the experiment. However, the graphs are model predictions based on fundamental principles of filtration, and as such help illustrate general trends involved in scaling.

### 5.2.1 Approach Velocity

In practice, filtration from the top to bottom bucket takes an average of 30 minutes for the 5 gallons of water. This leads to a flow of 5gal * 3.78L/gal * 1000mL/L * 1/30min * 1min/60sec = 10.5mL/sec through the filter. The diameter of the GAC filter for the GWI system is 4.8cm so the surface area of the filter was $\pi * 4.8^2 / 4 = 18cm^2$. The effective area through which water could flow is $0.59 * 18cm^2 = 10.6cm^2$, where 0.59 is the porosity. The velocity through the full-scale GAC filter was $10.5cm^3/sec / 10.6cm^2 =$ 1cm/sec.

To maintain the same approach velocity for the bench-scale model, the flow through the bench-scale GAC filter would be 1cm/sec multiplied by the effective area of the filter. The diameter of the graduated cylinder in the bench-scale GAC filter was 1.5cm. The surface area was $\pi 1.5^2/4 = 1.8cm^2$. The area through which water can flow is 0.59 *

$1.8cm^2 = 1.06cm^2$. The flow through the bench-scale GAC was 1cm/sec * 1cm2 = 1mL/sec throughout the experiment.

It was necessary to keep water velocity constant when scaling down in order that the microspheres be subject to the same advective forces. The velocity, and not the flow, was the parameter held constant in the scaling as it was felt that the velocity depends less on size than does flow. The flows of water through both bench scale filters were regulated by a stopcock connected at the end of the sediment filter and at the beginning of the GAC filter.

Fig. 5-2 is a graph of a simulation predicting the effect of removal efficiency with increasing particle diameter for three different approach velocities (Elimelech, p.357). The calculated approach velocity for the GAC filter (1cm/sec) 50 percent greater than the largest approach velocity displayed in the graph. Figure 5-2 shows that removal efficiency is less dependent on approach velocity and more dependent on particle size. For a 1cm/s approach velocity, there is a difference of 1-log removal efficiency between the surrogate (5.7μm) and an average-sized *Giardia* cyst (10μm). With the same approach velocity, there is approximately a difference of 0.5-log removal efficiency between surrogates and an average *Cryptosporidium* oocyst.

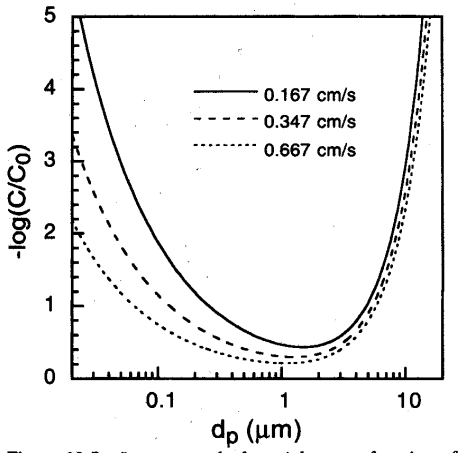


**Figure 5-2: Removal efficiency with increasing particle size for three different approach velocities (Elimelech, p.357)**

Fig. 5-3 shows a significant effect on removal efficiency with an increase in bed depth from 30cm to 180cm. According to the model, as bed depth decreases, the change in removal efficiency with particle size also decreases. Given that this study uses bed depths of 8cm and shorter, it is expected that removal efficiencies of *Giardia* cysts (7-12μm) and surrogates (5.7μm) will be similar.

The most significant parameter for removal efficiency is the carbon grain size. Fig. 5-4 shows a large increase in removal efficiency as grain size decreases from 1.8mm to 0.2mm. This is most likely due to the increase in the surface area to volume ratio as size decreases. The carbon used in both the GWI filter and the bench-scale model came from the same source, i.e. grain sizes are constant for both filters.

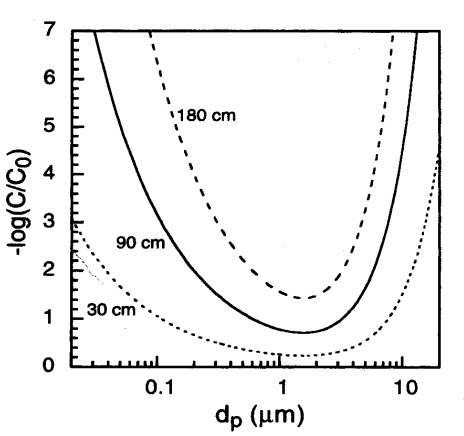


**Figure 5-3: Removal efficiency with increasing particle size for three different bed depths (Elimelech, p.359)**

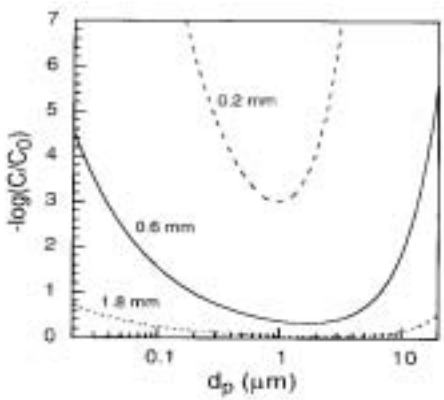


**Figure 5-4: Removal efficiency with increasing particle size for three different collector particle sizes (Elimelech, p.358)**

Given that the average collector particle size is held constant among actual and model filters, that there is a 1log removal efficiency difference between surrogates and *Giardia* cysts, and that the effect of bed depth on removal efficiencies for this study is small, it is assumed that the results from the experiments on the bench-scale filter can be scaled up to the GWI GAC filter. That is, given the removal efficiencies obtained from the model filters in the lab, it should be possible to predict approximate removal efficiencies for the full-scale GAC filters.

### 5.2.2 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.

### 5.2.3 Suitability of Surrogates

The question of whether the microspheres are suitable surrogates for (oo)cysts requires consideration of several properties, the most important of which are charge and size. *Giardia* has a zeta potential of –34.31mV at pH 7.1 in distilled water at an ionic strength of $2x10^{-3}$mM (Ongerth and Pecoraro, 1996). In distilled water with the same ionic strength, *Cryptosporidium* was found to have a zeta potential of –36.48mV at a pH of 7.3.

These zeta potentials decreased to zero as pH decreased. Since the charge on the surfaces of (oo)cysts are slightly negative, beads with negatively charged (carboxylate) functional groups were chosen to mimic their electrostatic behavior.

The average size of the microsphere is 5.7μm; the average size of the *Giardia* cyst is 10μm; and the average size of the *Cryptosporidium* oocyst is 4μm (Campbell, 2002; Polysciences, 2002). The difference in size should not affect the type of transport mechanism-all three sizes should be collected by interception (Hsu et al., 2001). The sifting characteristic of the GAC filter is considered unimportant in this study, as the particles used are three orders of magnitude smaller than the carbon grains. Straining is only considered a significant removal mechanism when the ratio of particle to grain size is greater than 0.2 (Elimelech, p.349). LeChavalier and Norton (1995) found that particles of a size greater than 3 microns were useful surrogates for counting *Giardia* cysts in secondary treatment.

For sediment filter removal, the size of the particle is a crucial characteristic, especially for particles with a size close to that of the pore spacing between the filter fibers. It is expected that the effluent concentrations for the surrogates will be greater than that of the *Giardia* cysts.

## 5.3 Stock Solution

Stock solution was made by placing 10 drops of the microspheres into 10mL of Q-water. Q-water was obtained by passing reverse osmosis water through the Aries Vaponics 110 volt system with one OR-1 and two MR-1 ion-exchange cartridges, through a TOC ultraviolet filter, and finally through a 0.22μm bacterial filter. The stock was kept refrigerated and sealed in a test tube when not in use as instructions suggested. From a well-mixed state in the 10-mL suspension, the particles completely settled by the next day. Care was taken to shake all bottles before sampling. Two standards were made from the stock solution; these were dilutions of 1:1000 and 1:500. The initial concentrations for all trials were 1:1000 dilutions (1mL of stock was added to 1000mL of solution). To simulate the pH measurements observed in Haitian water, sodium bicarbonate ($NaCO_3$) was added to the influent water in specific quantities noted below.

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. Trials were conducted within 20 minutes so that the resulting solution was not allowed to equilibrate with the atmosphere and the pH remained constant throughout the experiment.

## 5.4 Stock Solution Concentration

The concentration of particles was determined by using a Zeiss confocal axioscope to count the number of particles in a 1:500 dilution of the stock solution purchased from

Polysciences. The observed surrogates were observed as individual spheres; never were they observed to be aggregated to one another. The eyepiece has a magnification of 5x and the lens magnification was 10x. The field of vision was grided to be able to count surrogates in a measured area. A sample of the dilution was placed on the slide using a glass Pasteur pipette. The number of microspheres per grid averaged over five grids was 22.6. Each grid contained a volume of $10^{-4}$mL so the concentration of the 1:500 dilution was $2.26 \times 10^5$beads/mL. The concentration of the stock solution is therefore $2.26 \times 10^5$beads/mL x 500 or $1.13 \times 10^8$beads/mL. The influent concentration used in trials for this study was a 1:1000 dilution or $1.13 \times 10^5$beads/mL.

### 5.4.1 Many-Body Interaction

The low concentration of (oo)cysts in locations where they are present would suggest that there is effectively zero interaction amongst (oo)cysts in the bulk fluid during real-world filtration. This does not exclude interactions with other microorganisms or debris in the water. A criterion for many-body interaction was used to be certain that the quantity of surrogates would not be a factor in filtration, i.e. no contact between surrogates (Elimelech, p.294). A solution is considered to be dilute enough if $r_p >> (1+1/\kappa a_p)$, where $r_p$ is a dimensionless average spacing such that

$$r_p = (3/[4pC_o])^{1/3}/a_p \qquad (5.1)$$

where Co is the number concentration of particles in the bulk, $a_p$ is the particle radius, and $\kappa$ is the Debye-Huckel parameter--the inverse of which is the length of the diffusion layer. Typical values of $\kappa^{-1}$ range from 1-100nm. For this study we use Co = $1.13 \times 10^5$/mL, $a_p = 5.7 \times 10^{-6}$m, and $\kappa$ is assumed to be $30\text{nm}^{-1}$. Then $r_p = 2251 >> (1+1/\kappa a_p) \approx 1$ so that the solution is dilute enough that surrogates do not "sense" the presence of other surrogates in the bulk fluid. In this case the conditionality is effectively independent of variations in $\kappa$ values.

## 5.5 Fluorimeter

All samples were examined using a Perkin Elmer LS50B Luminescence Spectrofluorimeter, hereafter called a Fluorimeter. The instrument focuses light of a specific wavelength on to a sample. The fluorescent dye on the spheres becomes excited at a specific wavelength and emits light at a longer wavelength. A sensor in the fluorimeter is situated within the machine such that it receives light emitted from the beads at an angle orthogonal to the incident light. The computer program then plots the intensity of light as a function of the wavelength of light that is received. The y-axis is a measure of intensity. The x-axis is the wavelength of light received and has units of nanometers (nm).

Using a 1:500 standard of stock solution as a sample, an excitation scan was used to determine the wavelength at which the beads would become excited and fluoresce. The wavelengths of light tested ranged from 200-550nm. The wavelengths that resulted in

surrogate fluorescence ranged from 250-270nm. No other wavelength would cause the spheres to fluoresce, which is to be expected. The excitation wavelength was therefore fixed at 260nm throughout. For the 1:500 standard, emission maximum was approximately 200 at a wavelength of 308nm.

In addition to the excitation wavelength, the following properties of the scan method were also held constant throughout the experiment: the range of wavelengths scanned (220-800nm), the Excitation slit through which the incident light passed (5nm), the Emission slit (7nm), and the scan speed (240nm/min).

## 5.6 Graphs

For all samples containing beads, the corresponding graphs showed two sets of three peaks each (Fig. 5-5). The second set of peaks was translated 260nm to the right of the first set so that the first peak in the second set of peaks had a maximum at 520nm. The following description deals solely with the three distinct peaks, and disregards the second set starting at 520nm.

The first peak was the excitation peak. This peak represented scattering of incoming light by the spheres and was centered on 260nm. The second peak was centered on 285nm and its intensity throughout the trials was approximately 44units. The second peak was the secondary scattering known as Raman scattering and it was ignored during analysis. The third peak was centered on 308nm-this was 48nm longer in wavelength than the incoming light. This peak represented the amount of light emitted by the fluorescent beads, and was used as a measure of the number of beads in the volume of sample exposed to the incident light.

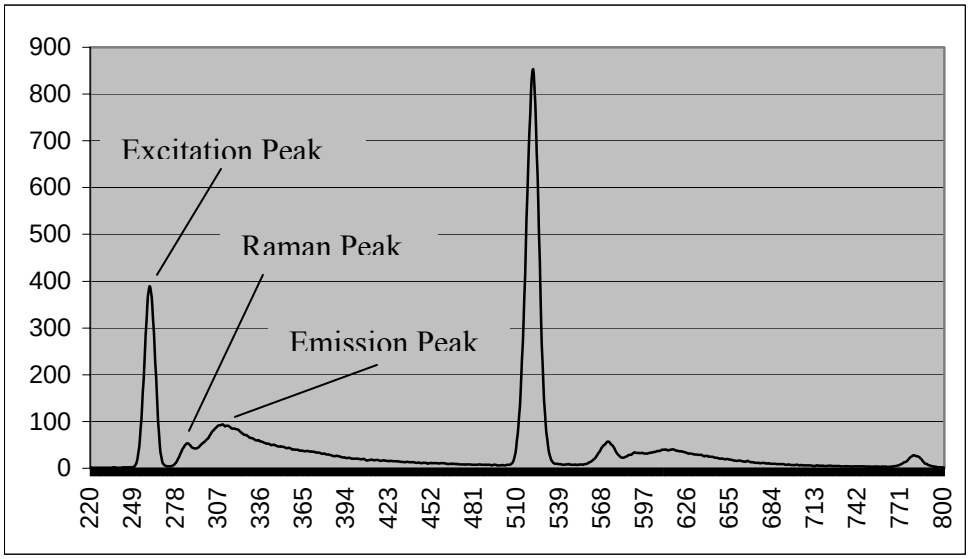


**Figure 5-5 Fluorimeter scan of 1:1000 standard**

Blank samples containing pure Q-water had intensity averaged at approximately 3 units at 308nm wavelength; this was considered the background noise of the fluorimeter itself. Blank samples containing Q-water and sodium bicarbonate showed a similar intensity. The 1:500 standards had an intensity averaged at approximately 200 units and the 1:1000 dilution had an intensity averaged at approximately 100 units. The intensities displayed on the graph were linear with sphere concentration.

## 5.7 Laboratory Experiments

Preparation for filter trials consisted of flushing the filters with a water solution of the pH that would be used in the experiment. Flushing volumes were approximately 1 liter for the bench-scale trials, and 5 liters for the full-scale trials.

For the bench-scale trials, the physical setup allowed for increments of 1-liter solutions to be created. A calculated mass of $NaHCO_3$ was first added to a 1-liter volume of Q-water to increase the pH to a desired value. The solution was stirred for approximately 30 seconds with a metal rod to increase dissolution. Next, 1mL of the stock solution was added to the water and the solution was mixed with a different metal rod to avoid contamination with subsequent volumes. For the full-scale trials, 1-liter volumes were created as noted above, and were emptied into the full-scale bucket.

A blank reading was taken everyday to establish the background noise of the fluorimeter. A standard reading was also taken every day to assure that the fluorimeter gave constant readings.

### 5.7.1 Test Variable; pH

The pH of the medium is considered an important factor in filtration as it contributes a great deal to the charging of both target and collector particles and hence to the forces between them. Ongerth and Pecoraro (1996) found the zeta potential of a *Giardia* cyst to be –40mV at neutral pH and it decreases in charge to –10mV at pH 3.5. For a negatively charged particles such as (oo)cysts, microspheres with carboxylate groups attached to their surfaces or carbon grains in the GAC filter, charge generally decreases as pH decreases. As these repulsive forces weaken, the attractive forces (London dispersion and Van der Waals) begin to dominate (Yao et al., 1971).

Consequently, pH was the central variable in this study. The range of pH values in Haiti was narrow—from 7.0 to 8.3 at the sources we sampled. Tests were thus conducted in this range of pH values.

# 6 Background

## 6.1 Collector Efficiency

The single collector efficiency is a ratio of the particle flux at the collector surface to the particle flux approaching the collector from upstream (Tobiason, 1989). Collector efficiency is highly dependent on the transport mechanism by which particles are delivered to the particle surface. There are three principle mechanisms by which particles are collected to a grain surface: Brownian motion, interception, and gravitational settling (Elimelech, p.348). For particles less than 1 micron in size, Brownian motion dominates. Such organisms--viruses, for example--travel by diffusion, thus the collector efficiency is probabilistic. For large particles with densities greater than the bulk fluid, transport is gravitation dominated. Collision efficiency in this case is measured by the distance between two particles. Particles of an intermediate size are transported to a target particle by interception. For this group of particles, to which both cysts and oocysts belong, collision occurs when the distance between the center of a target particle and the streamline-an imaginary line which goes through the center of the moving particle--is less than the sum of the radii of the two particles.

## 6.2 Theory of collectors

The clean-bed single collector efficiency, $\eta_o$, represents the initial rate of delivery of the particle to the collector surface (Elimelech, p.352). The total single collector efficiency is the sum of the collector efficiencies of each transport mechanism:

$$\eta_o = \eta_D + \eta_I + \eta_G \tag{6.1}$$

where $\eta_D$ is the collector efficiency for particles that travel by diffusion, $\eta_I$ is the collector efficiency for particles that travel by interception, and $\eta_G$ is the collector efficiency for particles that travel by gravity. The surrogates in this study were primarily transported to the collector by interception so $\eta_o = \eta_I$ was used throughout the study where

$$\eta_I = 1.5A_s(d_p/d_c)^2 \tag{6.2}$$

such that $d_p$ is the particle diameter (5.7μm), $d_c$ is the collector diameter (2mm), and $A_s$ is a parameter that accounts for neighboring beads such that

$$A_s = 2(1-p^5)/(2 - 3p + 3p^5 - 2p^6) \tag{6.3}$$

and

$$p = (1 - f)^{1/3} \tag{6.4}$$

where f is the porosity. The porosity of the GAC was measured to be 0.59 so that p = 0.74 and $A_s = 13.27$. This lead to a clean-bed single collector efficiency, $\eta_o = 6.47 \times 10^{-4}$.

The preceding analysis does not account for the small period of time during which there would be no flow through the filter and the single collector efficiency would be diffusion dominated.

## 6.3 Collision Efficiency

The collision efficiency, $\alpha$, is the fraction of collisions that result in attachment (Yao et al., 1971). Once a particle collides with a carbon grain, the removal of that particle from the bulk fluid is dependent upon it sticking to the grain, or the system's adhesion efficiency. This adhesion efficiency is dependent on the sum of forces a number of factors: the charge on the surface of the cyst, the charge on the grain, the hydrophobicity of the cyst, and the type of material on the grain. The collision efficiency of the spheres to the carbon grains is dependent on the partition coefficient, $K_d$.

## 6.4 Partition Coefficient, $K_d$

A test was conducted to assess the affinity of the microspheres for the GAC. A glass bottle was filled with 3 grams of carbon and 30mL of water at pH 7. The bottle was sealed and continuously in motion for 3.5 hours. The initial concentration of the water was 105.6 fluorescence, and the concentration after 3.5 hours was 55.4 fluorescence units. Assuming no spheres adsorbed to the sides of the bottle, the concentration adsorbed onto the carbon is $105.6\text{-}C_{water} = 105.6 - 55.4 = 50.2$. The partition coefficient, $K_d$ is (50.2/3g) / (55.4/30mL) = 9mL/g. After approximately four days, the concentration in the water was analyzed again such that, $C_{water} = 0.46$, $K_d = 13$mL/g. Essentially, this means that the GAC grains do not repulse the microspheres. To analyze the theoretical removal efficiency for the full-scale GWI filter, it is assumed that $\alpha \rightarrow 1$.

## 6.5 Theoretical Removal Efficiency

Yao et al. (1971) provides an equation to estimate the removal efficiency of a packed filter bed given the collision efficiency and collector efficiency of the system. The theoretical removal efficiency for the GWI is $1\text{-}\ C_e/C_o$ where $C_e/C_o$ is the ratio of effluent and influent concentrations given by:

$$C_e/C_o = \exp[-3/4 * \alpha_{exp} * (1-f)^{1/3} * \eta_o * L / a_c] \qquad (6.5)$$

where f is the porosity of the filter bed (0.59), $\eta_o$ is the clean bed collector efficiency calculated by equation 6.2 ($6.47 \times 10^{-4}$), L is the depth of the filter bed of the full-scale GAC filter (21cm), and $a_c$ is the diameter of the collector particle (0.10cm). Based on the theoretical model, the effluent to influent ratio for the GWI filter is approximately 92%

and the theoretical removal efficiency is approximately 8%. The theoretical calculation thus predicts significant breakthrough for the GAC filter used in the GWI purification system assuming interception as the sole means of collision and an ideal collision efficiency.

This analysis does not include any collision mechanisms other than interception and thus potentially underestimates removal efficiency. In the following section, direct observations of removal efficiencies are reported.

# 7 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.

## 7.1 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.

### 7.1.1 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. 7-1). 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.

### 7.1.2 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. 7-2). This test was conducted over a period of three days. Like the test at pH 7, the breakthrough gradually increase to 80 percent. Unlike the first test, this test showed less variability with the exception of an outlier at

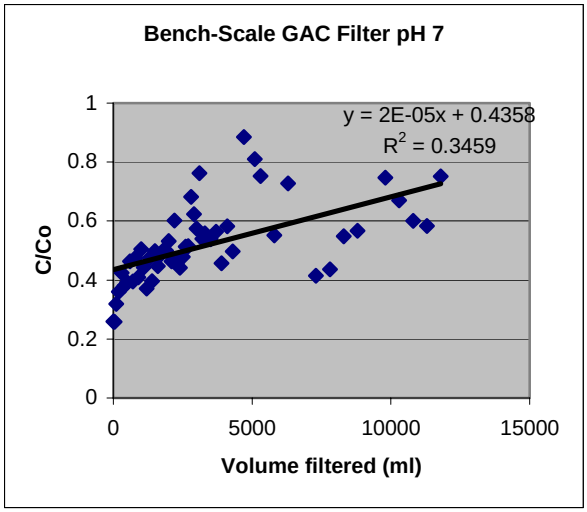


**Figure 7-1: Bench-Scale GAC at pH 7**

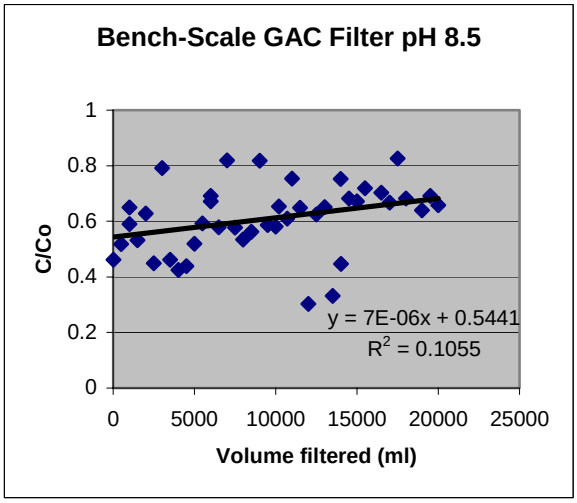


**Figure 7-2: Bench-Scale GAC at pH 8.5**

approximately 18.5 liters.

### 7.1.3 Bench-Scale GAC w/ 1 gram

A volume of 10 liters was run through the 1 gram of GAC. Initial effluent concentrations were 80 percent and remained 80 percent for the remainder of the test (Fig. 7-3). The bed depth of this filter was 1.5cm.

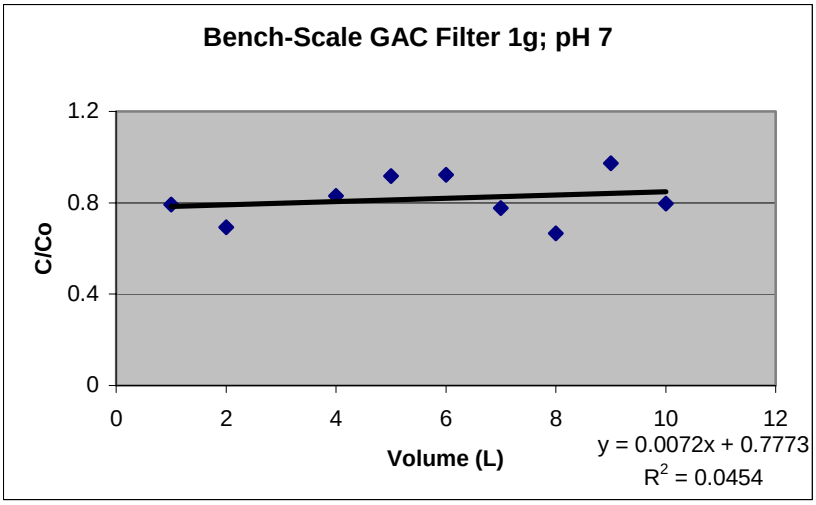


**Figure 7-3: Bench-Scale 1g GAC test at pH 7**

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.

## 7.2 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.

### 7.2.1 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. 7-4). 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.

### 7.2.2 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. 7-5). 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.

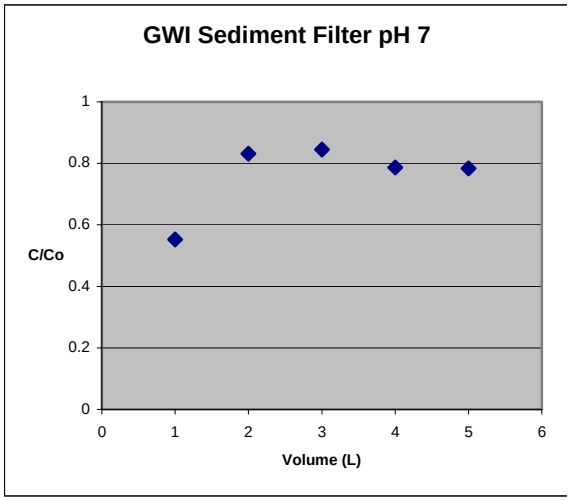


Figure 7-4: GWI Sediment Filter at pH 7

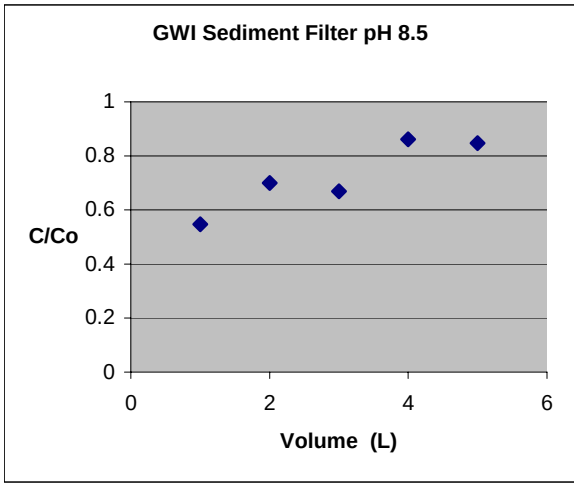


Figure 7-5: GWI Sediment Filter at pH 8.5

### 7.2.3 GWI Filter Run, pH 4.5-8.5

Fig. 7-6 shows an increase in removal as pH increased from 4.5 to 8.5. There was no flushing run preceding the run with spheres, and thus there was no correction for background noise. This may account for the effluent to influent ratio being greater than one for this test.

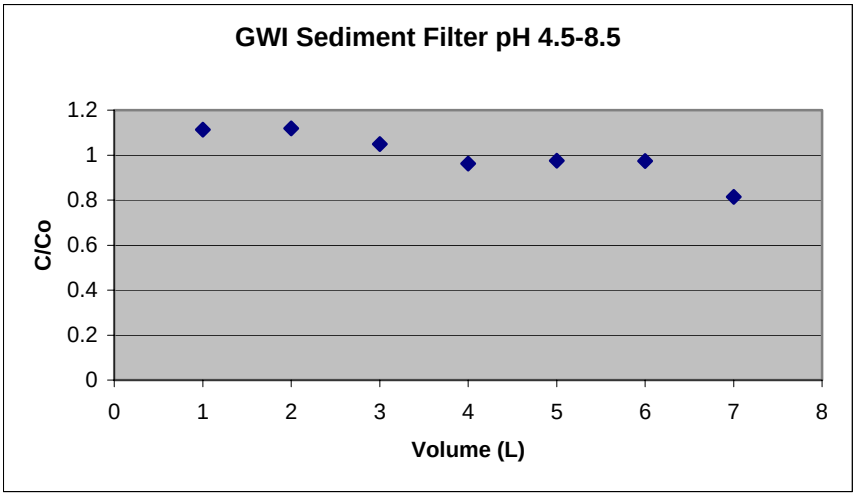


**Figure 7-6: GWI Sediment Filter at pH values from 4.5-8.5**

## 7.3 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.

### 7.3.1 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 (Fig.7-7).

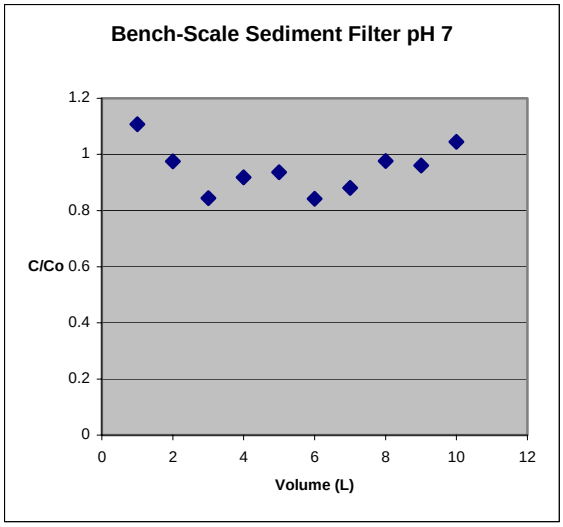


**Figure 7-7: Bench-Scale Sediment Filter at pH 7**

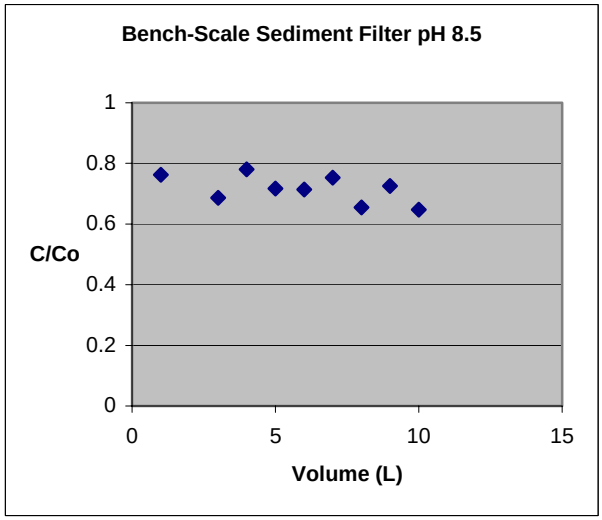


**Figure 7-8: Bench-Scale Sediment Filter at pH 8.5**

### 7.3.2 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 (Fig. 7-8). 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 7-1.

**Table 7-1: 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 |

# 8 Conclusion

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 from the results 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.

# 9 Bibliography

## 9.1 References


Addiss, D.G., MacKenzie, W.R., Hoxie, J.J., Graus, M.S., Blair, K.A., Proctor, M.E., Kazmierczak, J.J., Schell, W.L., Osewe, P., Frisby, H. Cicerello, Cordell, R.L., Rose, J.B. and Davis, J.P. *Epidemiologic Features and Implications of the Milwaukee Cryptosporidiosis Outbreak,* Protozoan Parasites and Water, The Royal Society of Chemistry, Cambridge: 1995, pp. 19-25.

Ahmedna, M.; Marshall, W.E.; Rao, R.M. 2000, *Production of granular activated carbons from select agricultural by-products and evaluation of their physical, chemical and adsorption properties,* Bioresource Technology, 71(2): pp. 113-123.

Ali-Shtayeh, M S; Hamdan, A H; Shaheen, S F; Abu-Zeid, I; Faidy, Y R. Feb. 1989, *Prevalence and seasonal fluctuations of intestinal parasitic infections in the Nablus area, West Bank of Jordan*, Annals of Tropical Medicine and Parasitology 83(1): pp. 67-72.

Amahmid, O; Asmama, S; Bouhoum, K; December 2001, Urban wastewater treatment in stabilization ponds: occurrence and removal of pathogens, Urban Water. Uncorrected Proof.

AnmweCamep, 1998, Haiti Global Village
http://www.haitiglobalvillage.com/sd-ancamep/bulletinboard.asp

Araj, G.F.; Abdul-Baki, N.Y.; Hamze, M. M.; Alami, S.Y.; Nassif, R.E.; Naboulsi, M.S. 1996, *Prevalence and etiology of intestinal parasites in Lebanon*, The Lebanese Medical Journal 44(3): pp. 129-133.

Aristide, Jean-Bertrand, March 2002. *Message from President Jean-Bertrand Aristide*, Haitian Embassy http://www.haiti.org/

Bella, S. W. H. and Tam, T. Y., September 1998, *Giardia and Cryptosporidium in sewage-contaminated* river waters**,** Water Research 32(9): pp. 2860-2864.

Blum, William, 1995, *Killing Hope: US Military and CIA interventions since World War II*, Monroe, ME: Common Courage Press.

Business Partners for Development Water and Sanitation Cluster, Port-au-Prince, Haiti: Restructuring public water services in shantytowns. October, 2001, http://www.bpd-waterandsanitation.org/english/prj_haiti.htm

Campbell, Andrew, Spring 2002
www.brown.edu/Courses/BI0054/handouts/gi1.pdf

Casemore, D.P. *The Problem with Protozoan Parasites,* Protozoan Parasites and Water, The Royal Society of Chemistry, Cambridge: 1995, pp. 10-18.

Chomsky, Noam, 1993. *Year 501: The Conquest Continues*, Cambridge, MA: South End Press.

CIESIN, 2002 Center for International Earth Science Information Network *Environmental Sustainability Index: Annex 5. Country Profiles*
http://www.ciesin.columbia.edu/indicators/ESI/ESI2002_21MAR02b.pdf

Common Dreams, May 2002. "Report Predicts Thirstier World", Farley, Maggie
http://www.commondreams.org/headlines01/0814-03.htm

Eagle Spring, 2002: Dann, Christopher. May 9, Eagle Spring Inc., Holly Hills, Fl.

Elice, Sara J. April 29, 2002. MIT, Ma.

Elimelech, M., Gregory, J., Jia, X., and Williams, R.A. 1995. *Particle Deposition and Aggregation: Measurement, Modelling and Simulation*, Jordan Hill, OX: Butterworth-Heinemann Ltd.

Envirochek, 2002, Owner's Manual.

Farmer, Paul and Bertrand, Didi, 2000. *Hypocrisies of Development and the Health of the Haitian Poor*, "Dying for Growth: Global Inequality and the Health of the Poor," Monroe, ME: Common Courage Press.

Finch, G., July 1996, *Water Industry Challenge—Waterborne Parasites—Part I,* Environmental Science & Engineering Magazine
http://www.esemag.com/0796/ parasite.html

Garratt, Scott, "On the road; don't take the pith," *Observer*, April 2002.

*Giardia* Standards, World Health Organization
http://www.who.int/water_sanitation_health/GDWQ/Microbiology/GWDWQMicrobiological2.html

Gift of Water, Inc. http://www.giftofwater.org/purifiers.html (accessed May 18, 2002)

Girdwood, R.W.A. 1995. *Some Clinical Perspectives on Waterborne Parasitic Protozoa,* Protozoan Parasites and Water, The Royal Society of Chemistry, Cambridge. pp. 3-9.

Grimason, A.M., Parker, J.F.W., and Smith, H.V. 1995. *Occurrence of Giardia Cysts in a Scottish Potable Water Supply and the Surface Water Source used for Abstraction*, The Royal Society of Chemistry, Cambridge. pp. 66-70.

Han Mooyounga, Lee Hyungkia, B, Desmond F. Lawlerc and Choi Sangild, 1997. *Collision efficiency factor in Brownian coagulation (Br) including hydrodynamics and interparticle forces,* Water Science and Technology 36(4): pp. 69-75.

Ho, Bella, S. W. and Tam, T. –Y. October 1998. *Giardia and Cryptosporidium in sewage-contaminated river waters*, 32(9): pp. 2860-2864.

Hsu, B.M. and Huang, C, Mar. 2002, *Influence of ionic strength and pH on hydrophobicity and zeta potential of Giardia and Cryptosporidium,* Colloids and Surfaces A: Physicochemical and Engineering Aspects 201(1-3): pp. 201-206.

Hsu, B.M., Huang, C., and Pan, J.R. Nov. 2001, *Filtration behaviors of Giardia and Cryptosporidium—ionic strength and pH effects,* Water Research 35(16): pp. 3777-3782.

Hu, Tai-Lee. March 2002, *Detection of Giardia cysts and Cryptosporidium oocysts in central Taiwan rivers by immunofluorescence assay*, Journal of Microbiology, Immunology and Infection, 35(1): pp. 68-70.

Human Rights Watch, World Report 2001: Haiti
http://www.hrw.org/wr2k1/americas/haiti.html

Hutton, P., Ashbolt, N., Vesey, G., Walker, J., Ongerth, 1995. *Cryptosporidium and Giardia in the Aquatic Environment of Sydney, Australia,* Protozoan Parasites in Water, The Royal Society of Chemistry, Cambridge: 1995, pp. 71-78.

ICDF, Investment & Lending Projects, *Drinking Water Distribution Project in Petionville, Haiti* http://www.icdf.org.tw/english/operations1-5.htm#3

Iturriaga, R; Zhang, S; Sonek, G J; Stibbs, H, July 2001, *Detection of respiratory enzyme activity in Giardia cysts and Cryptosporidium oocysts using redox dyes and immunofluorescence techniques,* Journal of Microbiological Methods, 46(1): pp. 19-28.

Jellison, Kristen. February, 2002, MIT, Ma. Personal Communication.

Jianhong Rena, Aaron I. Packman, and Claire Welty, October 2001. *Analysis of an observed relationship between colloid collision efficiency and mean collector grain size*, Colloids and Surfaces A: Physicochemical and Engineering Aspects 191(1-2); pp. 133-144.

Keas, B. 1999. http://www.msu.edu/course/zol/316/glamgut.htm

Kinsler, L., "Tampa reaches out to Haiti's poor" *Tampa Tribune,* March 2002.

Lantagne, D.S. 2001. *Trihalomethane Formation in Rural Household Water Filtration Systems in Haiti,* Cambridge, MA: MIT.

LeChevallier, M.W. and Norton, W.D. 1995. *Plant Optimization using Particle Counting for Treatment of Giardia and Cryptosporidium*, Protozoan Parasites and Water, Cambridge: The Royal Society of Chemistry, 180-187.

Liu, S G; Xie, Z. H. January 1994. *Protection of Vibrio cholerae from heating and chlorination by chitin,* Chinese Journal of Preventive Medicine, 28(1): pp. 16-19.

Malvern Instruments
Zeta Potential Theory
http://www.malvern.co.uk/Laboratory/zettheo.htm (accessed 5.18.2002)

Matheson, Z., Hargy, T. M., McCuin, R. M., Clancy, J. L., and Fricker, C.R. October 1998. *An evaluation of the Gelman Envirochek capsule for the simultaneous concentration of Cryptosporidium and Giardia from water*, Journal of Applied Microbiology, 85(4): pp. 755-761.

Nace, E.K., Steurer, F.J., and Eberhard, M.L. December 1999. *Evaluation of Streck Tissue Fixative, a Nonformalin Fixative for Preservation of Stool Samples and Subsequent Parasitologic Examination,* Journal of Clinical Microbiology, 37(12): pp. 4113-4119.

National Institutes of Health, 1998. *Giardia Trophozoite* Photograph
www.nih.go.jp/~tendo/atlas/ japanese/lambl.html

Nzeako, B C. December 1992. *Seasonal prevalence of protozoan parasites in Nsukka, Nigeria,* The Journal of Communicable Diseases 24(4): pp. 224-230.

O'Donnell, John, "Haiti languishes amid poverty," *Milwaukee Sentinel Journal,* December 2001.

Ogunba, E. O. September 1997. *The prevalence of human intestinal protozoa in Ibadan, Nigeria,* The Journal of Tropical Medicine and Hygiene 80(9): pp. 187-191.

Ongerth, J.E. and Pecoraro, J.P. March 1996 *Electrophoretic Mobility of Cryptosporidium Oocysts and Giardia Cysts*, Journal of Environmental Engineering, 122(3): pp. 228-231.

Ono, K; Rai, S K; Chikahira, M; Fujimoto, T; Shibata, H; Wada, Y; Tsuji, H; Oda, Y; Rai, G; Shrestha, C D; Masuda, K; Shrestha H, G; Matsumura, T; Hotta, H; Kawamura, T; Uga, S. Sep. 2001, *Seasonal distribution of enteropathogens detected from diarrheal stool and water samples collected in Kathmandu, Nepal,* The Southeast Asian Journal of Tropical Medicine and Public Health 32(3): pp. 520-526.

PAHO: Pan American Health Organization, Country Health Profile: Haiti http://www.paho.org/English/SHA/prflHAI.htm (Updated 2001)

Pall Corporation, Envirochek and Envirochek HV Sampling Capsules and Accessories http://domino.pall.com/www/Gelman%20Catalog.nsf/Microbiology/8183b62d5ba0b9a5852569a70074a9cd?OpenDocument&ExpandSection=1

Pape, J.W., Verdier, R.I., Boncy, M., Boncy, J., and Johnson, W.D. November 1994. *Cyclospora Infection in Adults Infected with HIV-Clinical Manifestations, Treatment, and Prophylaxis* Annals of Internal Medicine, 121(9): pp. 654-657.

Partners In Health, http://www.pih.org/index.html

Perch, M; Sodemann, M; Jakobsen, M S; Valentiner-Branth, P; Steinsland, H; Fischer, T K; Lopes, D.D.; Aaby, P; Mølbak, K. Dec. 2001, *Seven years' experience with Cryptosporidium parvum in Guinea-Bissau, West Africa*, Annals of Tropical Paediatrics 21(4): pp. 313-318.

Polysciences website (accessed 5.19.2002) http://www.polysciences.com/shop/product.asp?dept%5Fid=401525&pf%5Fid=19395

Rose, J.B., Lisle, J.T., and Haas, C. N. 1995. *Risk Assessment Methods or Cryptosporidium and Giardia in Contaminated Water,* Protozoan Parasites and Water, Cambridge: The Royal Society of Chemistry, pp. 238-242.

Seelig, B.; Bergsrud, F.; Derickson, R. February 1992, *Activated Carbon Filtration,* Treatment Systems for Household Water Supplies Activated Carbon Photograph: www.ext.nodak.edu/extpubs/h2oqual/ watsys/ae1029w.htm

Shiva, Vandana, 2002. *Water Wars: Privatization, Pollution, and Profit*, Cambridge, MA: South End Press.

Steele, A.D.; Geyer, A; Alexander, J.J.; Crewe-Brown, H H.; Fripp, P. J. Dec. 1988, *Enteropathogens isolated from children with gastro-enteritis at Ga-Rankuwa Hospital, South Africa,* Annals of Tropical Paediatrics 8(4): pp. 262-267.

Taylor, M.A. 1995. *Protozoan Parasites and Water: Veterinary Aspects*, Protozoan Parasites and Water, Cambridge: The Royal Society of Chemistry, pp. 246-249.

Tobiason, J.E. 1989. *Chemical Effects on the Deposition of Non-Brownian Particles,* Colloids and Surfaces, 39: pp. 53-77.

Torres, D.M.; Chieffi, P.P.; Costa, W A; Kudzielics, E. March-April 1999. *Giardiasis in nurseries supported by the São Paulo Municipal Prefecture*, Revista Do Instituto de Medicina Tropical de Sao Paulo 33(2): pp. 137-142.

Turquand, Greg. Feb 21, 2002. American Carbon, Inglewood, Ca. Personal Communication

*Understanding GWI Purifiers,* Gift of Water
http://www.giftofwater.org/purifiers.html

University of Cincinnati, Info Services. June 1998.
*EPA and University of Cincinnati Researchers Find Bacteria That Can Destroy Giardia Cysts*,
http://www.uc.edu/info-services/giardia.htm

University of Minnesota
College of Agricultural, Food and Environmental Sciences
Department of Soil, Water, and Climate *Retardation Factor or Coefficient*
http://www.soils.umn.edu/academics/classes/soil4216/lecture3_ieonly/Lecture3_2000_files/frame.htm

University of Minnesota, 2001. *Giardia* Cyst Photograph: *Electron Microscopy Facility*.
http://medem.med.umn.edu

University of Texas Library: Haiti Political Map 1999.
http://www.lib.utexas.edu/maps/americas/haiti_pol99.jpg

USAID, 1998. *Congressional Presentation: Haiti FY 1998*
http://www.usaid.gov/pubs/cp98/lac/countries/ht.htm

USAID, 2001 *Haiti: FY 2001 Program Description and Activity Data Sheets*
http://www.usaid.gov/pubs/bj2001/lac/ht/haiti_ads.html#ads

USEPA, December 1998. United States Environmental Protection Agency, *Interim Enhanced Surface Water Treatment Rule*, Federal Register Document
http://www.epa.gov/safewater/mdbp/ieswtrfr.html

USFMA, 2002, U.S. Foreign Military Assistance, Economic Support Fund (Updated 2002) http://www.fas.org/asmp/profiles/aid/aidindex.htm

Van Loosdrecht, M. C. M.; Lyklema, J.; Norde, W.; Schraa; G., Zehnder, A. August 1987. *Electrophoretic Mobility and Hydrophobicity as a Measure to Predict the Initial Steps of Bacterial Adhesion,* 53(8): pp. 1898-1901.

Vressman, W.; Hammer, M.J. *Water Supply and Pollution Control*, Harper Collins, New York, NY: 1993.

Ward, H D; Alroy, J; Lev, B I; Keusch, G T; Pereira, M September 1985. *Identification of chitin as a structural component of Giardia cysts,* Infection and Immunity, 49(3): pp. 629-634.

Warwick, Phil. May 2002. Gift of Water Inc., Fl. Personal Communication.

WHO, 1993. World Health Organization, *Water and Sanitation: Guidelines for Drinking Water quality* http://www.who.int/water_sanitation_health/GDWQ/Microbiology/GWDWQMicrobiological2.html (accessed 5.20.2002)

Wilson, Scott, "In Haiti, in a stalled turn toward democracy, Silencing of opposition blocks foreign aid that could ease unrest and poverty," *Washington Post,* Feb. 2002.

World Bank, Februrary 2002a Country Assistance Evaluation: Haiti, Report No. 23637 February 2002. Operations Evaluation Department; Document of the World Bank http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2002/03/22//000094946_02030704005684/Rendered/INDEX/multi0page.txt

World Bank 2002b Development Data Group, *ICT at a Glance: Haiti*, The World Bank Group.

World Bank, 1999 Human Development Network, The World Bank Group http://devdata.worldbank.org/hnpstats/query/countries.htm

World Bank, Access to Safe Water, 2000 http://www.worldbank.org/depweb/english/modules/environm/water/chart1.htm

Yao, K.M., Habibian, M.T. and O'Melia, C.R. 1971. *Water and wastewater filtration: concepts and applications.* Environmental Science and Technology 5: pp. 1105-1112.