EVALUATION OF PROCESS CHANGES ON FINISHED WATER QUALITY FOR GIFT OF WATER SYSTEM

A Thesis

Submitted to the Faculty

of

Purdue University

by

Amanda C. Costello

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Civil Engineering

August 2013

Purdue University

West Lafayette, Indiana

ACKNOWLEDGEMENTS

I would like to thank the people at Gift of Water for allowing me to assist with this project. I learned so much in my research, my lab work, and my travels that I will carry with me for the rest of my life and my career. I would like to specifically thank Laura Moehling for all her help and guidance throughout this project. Her dedication to this organization is inspiring, and it was an honor to work with her.

I would also like to thank my advisor, Professor Ernest R. Blatchley III for all his help with this project and with my degree. His intellect, his approachability, and his coaching skills were invaluable to me throughout my college career.

I would also like to thank my committee members, Chad T. Jafvert and Bruce Applegate, for their help with this project.

I would also like to thank all the people who helped me in the lab. Thank you to Mehrnaz Afifi, Shih-Chi Weng, and Angela Ortiz for teaching me how to use the instruments in the lab. Thank you to Kevin Canida for helping me to haul water from the Wabash River for experimentation. Thank you to Bruce Applegate and Phil Myer for helping me with the inactivation assays. Furthermore, thank you to David Henderson for allowing me to set up experiments at the West Lafayette Wastewater Treatment Plant.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure Page

Figure Page

LIST OF TABLES

Table Page

Table Page

ABSTRACT

Costello, Amanda C. MSCE, Purdue University. August, 2013. Evaluation of Process Changes on Finished Water Quality for Gift of Water System. Major Professor: Ernest R. Blatchley III.

Gift of Water (GOW, est. 1995) is an Indiana based nonprofit organization dedicated to providing clean drinking water for communities in Haiti. Their system involves prechlorination, followed by a string filter, granular activated carbon (GAC), and then post-chlorination. The initial design of the GOW system included a polypropylene string filter with a nominal pore size opening of 5 μm, which has been changed to one with a nominal pore size opening of 1 μm. Experiments were conducted to compare the original system with the modified system and to quantify the effectiveness of the systems to produce clean drinking water, including measurements of volumetric flow rate, *E. coli* removal efficiency, turbidity, free, total and combined residual chlorine concentrations, volatile disinfection by-products (DBPs), and UV absorbance at 254 nm. The clogging rates for the 1 μm and the 5 μm filters were measured to quantify the sustainability of the two filter types. Inactivation assays for bacteriophage as surrogates for human viruses were also performed on the GOW system with a pure and a natural water source. Finally, source water quality data, including turbidity and viable *E. coli* concentrations, from communities where GOW systems are used were collected during a trip to Haiti.

Little difference was noted in the volumetric flow rates between the two string filters throughout the course of the experiment. Bacterial inactivation was consistently effective; both filter types successfully removed the *E. coli* from the source water. Both filters were able to remove a large fraction of the colloidal particles from the water. The effluent turbidity values for both filter types fell below 5 NTU when the influent water was less than or equal to 12 NTU.

Free and total chlorine concentrations decreased in the final water samples for both filter types. The activated carbon filters were effective in removing most of the free and total chlorine from the first chlorine dose. The combined chlorine concentration measurements were substantially less than the free chlorine concentration measurements. Chloroform ($CHCl_3$) was the only DBP observed to be present above the detection limit in the chlorinated water samples. The chloroform concentrations measured in the effluent water samples from the 1 μm and the 5 μm filters were all well below the Maximum Contaminant Level of 80 μg/L for Total Trihalomethanes, as established by the US EPA. The absorbance at 254 nm generally decreased from intermediate to final water samples. The UV-absorbing compounds are successfully removed by the filtration or adsorption in the GAC, or by the reactions in the secondary chlorine dose.

The clogging rates between the two filters were nearly identical. The 1 μm filter allowed an average of 4037 liters of water through the filter, and the 5 μm filter allowed an average of 3828 liters of water through the filter before clogging occurred. This corresponds to approximately 202 runs for the 1 μm filters and 191 runs for the 5 μm filters.

The GOW system achieved over seven logs of inactivation for the φS1 phage suspension and over four logs of inactivation for the T4 phage suspension when used with Milli-Q water. When used with Wabash River water, the GOW system achieved approximately three logs of inactivation for the φS1 phage suspension and less than one log of inactivation for the T4 phage suspension. The GOW system was not effective at inactivating human virus surrogates in this natural water source.

Water quality data from six water sources were collected in Haiti. The *E. coli* concentrations in the samples ranged from 1.5 most probable number (MPN) of *E. coli* per 100 mL of the sample to 48.3 MPN of *E. coli* per 100 mL of sample. The turbidity measurements ranged from 0.19 NTU to 6.64 NTU.

CHAPTER 1. INTRODUCTION

1.1 Scope of Problems

Access to adequate water supply and proper sanitation is considered a fundamental need and a human right. The World Health Organization (WHO) has established several guidelines, specific to that access. Firstly, 50-100 liters of water per person per day are needed to ensure that the basic needs of a person can be met. Furthermore, this water must be free from pathogens, chemical contamination, and radiological hazards that can threaten human health. The water also should have acceptable color, odor and taste for the users. The WHO claims that water should also be physically accessible to the users, or within 1 km of a home for collection. Finally, water should be an affordable commodity, and should therefore not exceed 5% of a household's income (United Nations, 2010).

These guidelines are not met in many developing countries today. According to the WHO, roughly 800 million people in the world lack access to an improved water supply, and 2.4 billion people lack access to improved sanitation. According to UNICEF, an improved water source is "protected from contamination, particularly faecal matter," and an improved sanitation facility "ensures hygienic separation of human excreta from human contact," (UNICEF, 2013). Those living in developing countries, areas of

extreme poverty, and rural regions are affected most by the statistics above (WHO, 2000). Since 1990, 2.1 billion people have gained access to an improved drinking water source, and 1.9 billion people have gained access to sanitation facilities. Despite this progression, a majority occurred in urban areas. As of 2011, approximately 83% of the world's population lacking access to a safe drinking water source lived in rural areas, while 71% of the world's population lacking access to sanitation lived in rural areas (WHO and UNICEF, 2013).

Figure 1 displays the drinking water trends in developing regions around the world. Only 6% of the water in Latin America and the Caribbean comes from unimproved sources, which is far better than other developing regions, as shown in the figure (WHO and UNICEF, 2013). Haiti is far behind the rest of the Latin America and Caribbean region, however. According to the Global Water Supply and Sanitation Assessment Report on 2000, more than 75% of the people in Latin America and the Caribbean have water supply and sanitation coverage, whereas Haiti has 46% water coverage and 28% sanitation coverage (WHO, 2000).

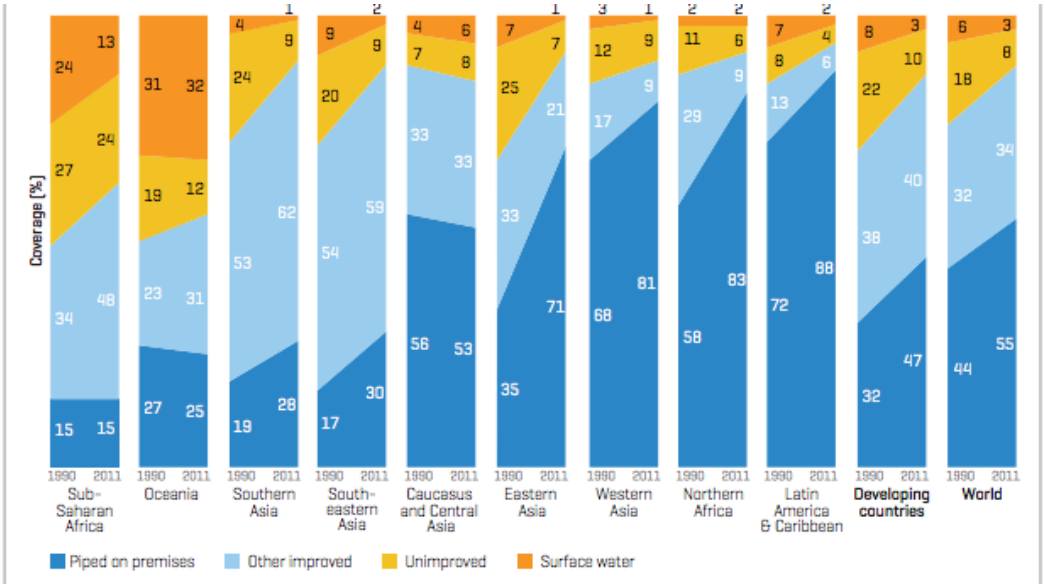

Figure 1: Drinking water coverage trends by developing regions and the world, 1990-2011 (WHO and UNICEF, 2013).

1.2 Haitian History

Historically, the Republic of Haiti has faced many hardships and times of turmoil, which have led the country to its current state of desolation. Haiti is located on the island of Hispaniola in the Caribbean, directly to the West of the Dominican Republic, as shown in Figure 2. The country occupies about 27,750 square kilometers, and the current population is 9.89 million people (CIA, 2013). The capital of Haiti is Port-au-Prince, and the two languages spoken in the country are Creole and French.

Figure 2: Map of Hispaniola.

Christopher Columbus discovered Haiti in 1492, when it became a Spanish colony. By 1700, the French seized control of the country, using the area to cultivate coffee and sugar. Between 500,000 and 700,000 African slaves occupied Haiti at that time. After a series of rebellions by the black slaves, Haiti declared independence from France on January 1, 1804, after which Jean-Jacques Dessalines, a former slave, became the Emperor. After his assassination, Henri Christophe took over Northern Haiti and Alexandre Petion took over Southern Haiti. After they passed away, General Jean-Pierre Boyer came into power from 1822 to 1844. The economy in Haiti failed after Boyer paid off France to grant their independence, making Haiti the first independent Caribbean state. The agricultural output that held the economy together was no longer attainable after this event, thus reducing the country's profits. After Boyer was forced out of the country for charges of corruption, Hispanic forces gained control of the country until 1915, when General Guillaume Sam gained presidency. He executed 167 political prisoners, leading to a rebellion by the Haitians, in response to which US troops were forced to intervene. American administrators then ran the Haitian government until 1934

(Haggerty, 1991). The country was under the harsh dictatorship of Francois Duvalier and his son Jean-Claude Duvalier from 1957-1986, during which time tens of thousands of people were killed for opposition to their rulers. In 1990, former priest Jean-Bertrand Aristide was elected, but was overthrown by the military shortly after. Although many of his supporters were killed during this rebellion, he was restored to the office until 2004. Problems with drug trafficking, gangs, and political groups left the country in a vulnerable position. President Michel Martelly and Prime Minister Laurent Lamothe, who are adamant about helping the country to overcome its many shortcomings, now lead the country (BBC, 2012).

1.3 Problems Specific to Haiti

Haiti is ranked as having the 25th worst access to improved drinking water sources in the world. 37% of the population lacks access to improved water sources, 83% of the population lacks access to improved sanitation, and 29% of the children under the age of 5 are malnourished, or have experienced stunted growth. There are about 45,000 deaths in children under 5 years old per year, and the adult life expectancy is 62 years (Onuoha, 2012).

The Human Development Index (HDI) is a composite measurement based on life expectancy, education, and gross national income (UN, 2013). Haiti is the poorest country in the Western Hemisphere, with a HDI of 0.456, ranking 161st, out of 187 countries. For comparison, the average world HDI is 0.694 (UN, 2013). According to the World Bank, over half of the population lives on less than US $1 per day, and about 80% of the population lives on less than US $2 per day (The World Bank, 2013). Being

so poor, it is hard for the country to provide the infrastructure needed for safe drinking water and sanitation services. It is also extremely difficult for the country to bounce back from natural disasters.

In the last five years, several major natural disasters have severely impacted Haiti. In 2008, three hurricanes, Gustav, Hanna, and Ike, passed through the country, killing about 800 people and destroying about 60% of the country's harvest. Haiti is very heavily deforested, with about 2% of its original tree coverage, so the smallest storm can wash away the topsoil in the country, leading to mudslides and flash floods, which is why events such as these are so catastrophic (Carroll, 2008). Agricultural production and logging for charcoal and firewood were the main causes of this deforestation. It is estimated that 500 kg of firewood is used per capita each year in Haiti. Charcoal and firewood supply the country with 80-90% of its total energy (Mclintock, 2003).

In January 2010, a magnitude 7.0 earthquake occurred in Haiti, which killed approximately 316,000 people and injured many more. This earthquake displaced about 1.5 million people, some of whom are still living in tents and camps to this day (Leger, 2012). During a response trip to Haiti in October of 2010, it is believed that the United Nations peacekeapers from Nepal inadvertently brought a very toxic strain of Cholera, which contaminated the country's already poor water supply (BBC, 2013). The cholera outbreak that followed was one of the largest in history, infecting about 650,000 people and killing more than 8,000 Haitians to date (Linn et al., 2013). According to the WHO, "Cholera is an accute diarrhoeal infection caused by ingestion of food or water containing the bacteria *Vibrio cholerae*," (WHO, 2012). This disease can kill the infected person

within hours of infection. The rapid spread of this disease was inevitable due to the lack of access to safe drinking water and sanitation in the country, which worsened after the earthquake (Leger, 2012).

Furthermore, tropical Storm Isaac and Hurricane Sandy passed through Haiti in 2012, killing more residents and further damaging their infrastructure. Since so many Haitians were still residing in tents and camps after the earthquake, they were greatly affected by the flooding and mudslides that came from these storms. Many tents and homes were flooded with raw sewage (UN, 2012). These natural disasters are preventing the Haitian population from progressing, and they are worsening the living conditions for large segments of the country's population.

1.4 Implications of Lack of Safe Water Access

1.4.1 Chronic Illness

There are many negative health effects associated with poor water supply and sanitation. Some waterborne diseases that are transmitted through drinking contaminated water sources include diarrhea, typhoid, viral hepatitis A, cholera, guinea worm infection, and dysentery (WHO, 2013). According to the Global Water Supply and Sanitation Assessment Report, roughly 4 billion cases of diarrhea resulting in 2.2 million deaths each year are attributable to poor water supply and sanitation. These deaths occur most frequently among children under the age of five, and account for 15% of all child deaths in developing countries (WHO, 2000). This is greater than the death count in children from HIV/AIDS and malaria combined (WHO, 2013).

1.4.2 Stunted Child Development & Poverty

Waterborne diseases among children can lead to stunted growth rates and malnutrition, as well as poor school attendance and performance (Kramer & Tobin, 2003). Malnutrition and inadequate access to a safe water supply and proper sanitation are directly linked to poverty throughout the world. Some children are forced to drop out of school when they get sick, which forces these individuals into lower-income jobs or poverty later in life. This can also reduce the potential economic growth of a country through limited potential of future generations. Furthermore, when the general population contracts these waterborne illnesses, they are forced to work less or quit their jobs, which can cause disastrous effects for their families, as well as the local economies (Marini & Gragnolati, 2003). Since profits from the local economies are essential to obtain the proper infrastructure for clean water or proper sanitation, it is highly unlikely that these communities will ever be able to resolve major sanitation problems themselves. This phenomenon is commonly referred to as the poverty cycle (The World Bank, 2012)

1.4.3 Effects on Women and Children

Women and children are the primary carriers of water in areas where water needs to be fetched, and it is estimated that these individuals spend about 40 billion hours each year doing so (Onuoha, 2012). The paths taken to the various water sources may be long and the conditions dangerous. According to UNICEF, women and children in developing countries walk an average of 6 kilometers per day to fetch about 20 liters of water (UNICEF, 2012). The loads are extremely heavy, and these water sources are often unsafe for consumption. Behind children, pregnant and lactating women are the most

vulnerable to waterborne diseases (WHO, 2013). Figure 3 shows a picture of a Hatian child fetching water for her family on their donkey.

Figure 3: Haitian child fetching water for her family.

1.5 Gift of Water

1.5.1 History

Gift of Water (GOW) is a nonprofit organization that has been dedicated to the provision of filtered and clean drinking water for developing countries (primarily Haiti) since May 1995. Following several medical mission trips, the founder, Thomas P. Warwick (Phil), realized that contaminated water was likely the cause of many illnesses throughout the country. To help with this issue, he gathered a team and developed a durable, inexpensive water filtration system, based on a design from the British military of the 1800s. After obtaining several grants, the organization was able to expand to over 100 communities by the end of 2007. The economic downturn in 2008, however, led to financial instability, causing the original management to shut down the organization in

December 2009. After learning of this, Pete Murphy and Laura Moehling, members of the current board of directors for GOW, took it upon themselves to restart the organization so that the systems could continue to be implemented across Haiti. The home base for GOW is now in Carmel, Indiana (Gift of Water, 2013).

The GOW filtration system involves prechlorination to accomplish disinfection and oxidation, physical separation (filtration) and adsorption to remove particulate and dissolved contaminants, and then post-chlorination to accomplish additional disinfection and for provision of a stable disinfectant residual, which is important for safe water storage. To implement these systems across Haiti, GOW developed an established operating model, as outlined in section 2.4.1, in partnership with Haitian communities. The combined success of the water treatment systems and the operating model in Haiti has positioned GOW to effectively provide the Haitian communities with safe water.

1.5.2 Mission Statement

Gift of Water's mission statement, as outlined on their webpage, is to "provide filtered, clean and available drinking water to improve the health of impoverished children and families through community development and simple technologies in developing countries" (Gift of Water, 2013). One objective of that mission is to provide a system that allows Haitian users to obtain clean, safe drinking water which meets international health standards. Another is to diminish waterborne illnesses in Haitian children in order to provide them with a better future. Educating the Haitian users about proper use of the systems and proper drinking water standards are also important objectives for the GOW team so that their systems can be used properly and effectively. The GOW team strives

for eventual self-sustainability in the Haitian communities they serve so that all the people of Haiti may one day have access to safe drinking water. The final objective for GOW is continuous improvement of the water filters, so that the effluent water is of the best possible quality for the Haitians.

1.5.3 Existing Presence in Haiti

After being established in 1995, GOW expanded to serve over 120 villages across Haiti. Following the change in ownership, GOW has established or re-established their presence in over 50 communities, installing of over 10,000 new systems and replacing another 20,000 components for maintenance. Furthermore, over 8 million chlorine tablets have been distributed across Haiti so that the systems can continue to be used. Today, under the new direction, although the GOW presence across the nation is smaller than before, the program is continually expanding, with hopes to again reach over 100 communities in the next couple of years. Figure 4 shows a map of the sites in Haiti where GOW is active today (Gift of Water, 2013).

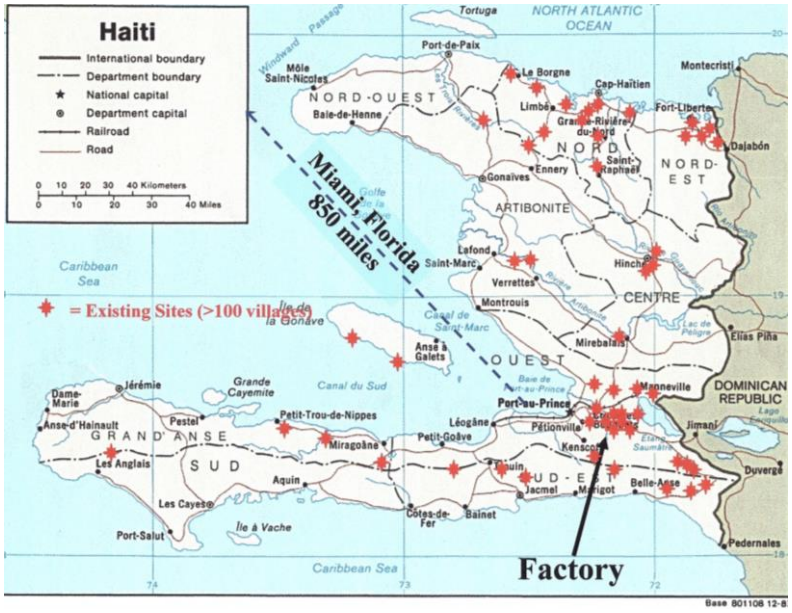

Figure 4: Gift of Water presence in Haiti (Gift of Water, 2013).

1.6 GOW System Process Changes

As previously described, the GOW system includes a physical separation (filtration) process in order to remove the particles from the water. The initial design of the GOW system included a polypropylene string filter with a nominal pore size opening of 5 µm. Following the change in direction, the new GOW team wanted to alter this design to improve upon the systems so that higher quality effluent water could be created. In order to achieve this goal, the original string filter was changed to one with a nominal pore size opening of 1 µm. This smaller pore size opening was intended to aid the systems in removing smaller sediments and some parasites that the 5 µm string filters might have missed.

1.7 Project Objectives

The primary objective of this project was to characterize the effects of process changes that were made to the GOW system and to quantify the effectiveness of the systems. As described above, these changes were expected to improve finished water quality, but it was unclear how these changes would affect the long-term performance of the system. Therefore, experiments were conducted at Purdue University to compare the original system to the modified system. The following list of measurements were conducted on water samples from the GOW systems:

- Volumetric flow rate through the string filter
- *E. coli* concentrations
- Turbidity
- Free, total, and combined chlorine
- UV absorbance at 254 nm
- Volatile disinfection by-products (DBPs)

For another phase of the project, 1 μm and 5 μm string filters were continuously fed secondary effluent from the West Lafayette Wastewater Treatment Plant (WWTP) as a means of monitoring the clogging rate for the new and old string filters. The goal of this experiment was to provide a direct comparison of clogging rates in the two filters; this is expected to provide information that field technicians can use in the future to address filter clogging. It is important that GOW is prepared with replacement parts so that the Haitian users do not abandon their units due to frustration.

An additional experiment was performed to examine the ability of these systems to remove and/or inactivate human viruses. Bacteriophage were applied intermittently as surrogates for human viruses to characterize viral inactivation. Stock suspensions of phage were prepared and used to seed the filters. The concentration of infective phage was measured in influent and treated water using standard plaque assays.

Lastly, from June 10th to June 15th, the author was able to travel to Haiti for one week with GOW to obtain source water quality data to compare with the raw water used for laboratory experiments. The author also aided in the educational efforts and the system distribution to the receiving households. Participants on this trip included Laura Moehling, Natalie Wilhelm (a Master's student at Tufts University), the author and her mother. The group worked with three different communities during their week in Haiti: Belladere, Croix Fer, and Dos Celle.

CHAPTER 2. LITERATURE REVIEW

2.1 Multiple Barrier Concept

The multiple barrier concept has been employed worldwide for centuries to ensure that drinking water production is safe and efficient. Multiple barriers for water treatment ensure that the final effluent water will be safe for consumption, even if one of the barriers were to fail. The barriers traditionally include "protection of source water, coagulation, flocculation and sedimentation, filtration, disinfection, and protection of the distribution system," (LeChevallier & Au, 2004). Additional stages for filtration or disinfection are often added to improve upon the final water quality, if deemed necessary.

A common water treatment sequence for surface water supplies in developed countries includes coagulation, flocculation, sedimentation, filtration, disinfection, and storage. These steps vary based upon the source water quality in the area. Coagulation involves the introduction of chemicals into the water, which change the surface chemistry of colloidal particles and also water chemistry, so as to destabilize colloidal suspensions. The destabilized particles are then subjected to flocculation, where particle-particle collisions lead to growth of particle size. These combined particles are then able to settle out of the water during sedimentation. Next, the water flows through a filtration step, which allows separation of many of the particles in the water that were not removed in

the preceding steps. Then, the water is disinfected, usually through the addition of chlorine, to kill or inactivate (pathogenic) microorganisms in the water. Finally, the water is stored in a safe location, free from possible recontamination, before distribution to the users (EPA, 2012). This typical treatment sequence includes steps for both filtration and disinfection, which covers multiple barriers to ensure that the water is safe from any possible contaminants in the water that are unsafe for consumption.

2.1.1 John Snow Epidemiology Case Study

In 1854, following a severe cholera outbreak in London, John Snow hypothesized that the disease was being spread through the local water distribution system. Prior to this outbreak, it was generally believed that the disease was spread through air pollution. Snow studied the pattern of disease in the area and linked the spread of the disease to the users of a certain water pump in the area, the Broad Street Pump. Figure 5 illustrates the locations of cholera deaths throughout the neighborhood. A majority of the deaths that resulted in this epidemic occurred in the direct vicinity of that pump, where most of the residents drew their water. There were 10 deaths that occurred in an area that was closer to another pump, but Snow discovered that those families were using the Broad Street Pump due to taste preferences. Some other displaced deaths occurred in children that went to school near the Broad Street Pump. Researchers later discovered that this well was dug only three feet from a cesspit that had begun to leak. The contamination, therefore, came from that source. Once that water source was cut off, the cases diminished extensively, proving the source of contamination, and also proving that diseases such as cholera can be spread through water (Frerichs).

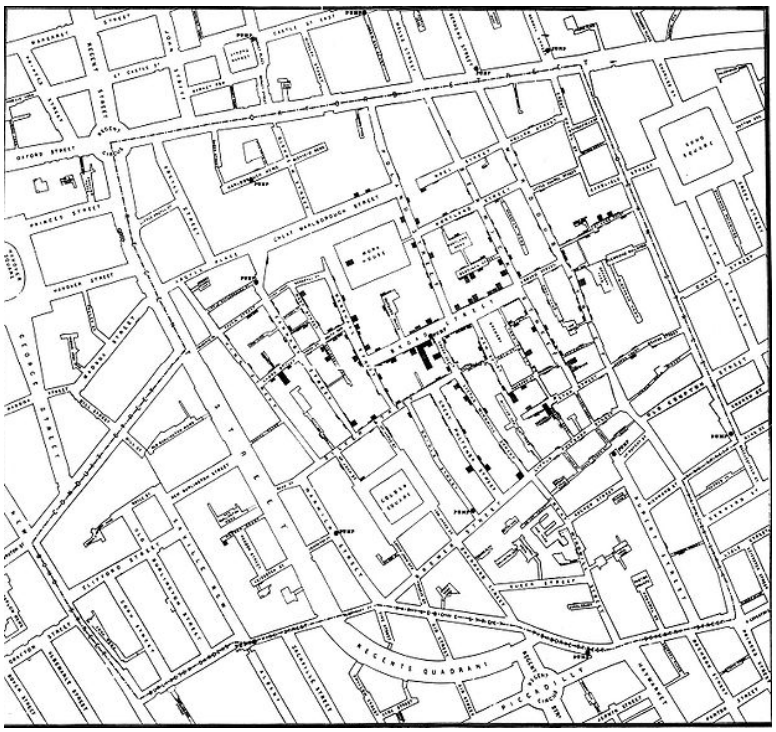

Figure 5: Map of cholera deaths in the 1854 epidemic (Frerichs).

2.1.2 Philadelphia Typhoid Case Study

Between 1860 and 1906, over 27,000 people died in Philadelphia due to typhoid fever, a disease caused by the bacterium *Salmonella typhi*. This bacterium is spread through the ingestion of food or drink that has been contaminated by the excrement of other infected people. After the John Snow epidemiology case study in 1854, it was proven that these diseases were, in fact, commonly spread through the local water supply. At the time of this typhoid epidemic in Philadelphia, both household and industrial waste were routinely dumped into the local rivers with no treatment, and that same water was used for drinking water for the area. Once the public health officials recognized that the water supply was the source of this infection, plans were put into place to remove or inactivate bacterial pathogens from drinking water to protect public health. Between 1900 and 1911, five

slow sand filtration plants were constructed throughout the city. The project was costly, amounting to $28 million, but the typhoid deaths in the city were greatly reduced through the removal of the bacteria. After the addition of chlorination in the water treatment process in 1914, the typhoid mortality rate in Philadelphia dropped again to a tiny fraction of what it was before this infrastructure was put into place. Figure 6 displays this death rate in the area from 1860 to 1936, highlighting the addition of filtration and chlorination to the water treatment processes (Levine, 2011).

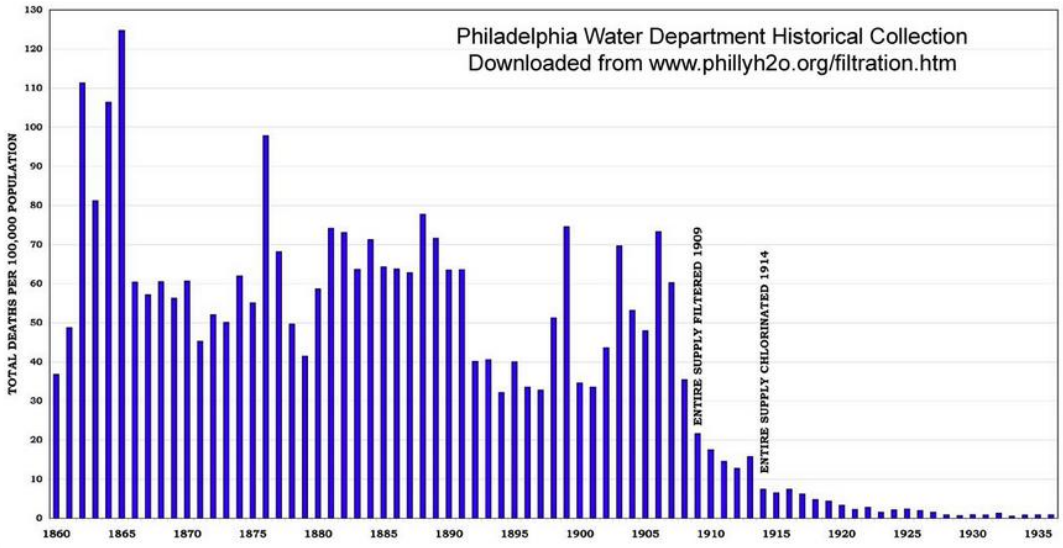

Figure 6: Death rate from typhoid fever in Philadelphia from 1860-1936 (Levine, 2011).

This incident in Philadelphia proved further that waterborne disease outbreaks, such as typhoid fever, can be greatly reduced if proper water treatment processes are applied. The multiple barrier approach applied in this instance was able to bring about substantial reductions in the death rates from typhoid fever.

2.2 Previous Work with GOW System

Other research has been done with these GOW systems in the past. In May of 2001, Daniele S. Lantagne submitted a thesis titled *Trihalomethane Formation in Rural Household Water Filtration Systems in Haiti*. Lantagne investigated the raw source water quality in Haiti at that time and collected finished water samples from the existing GOW filtration systems in Haiti for analysis at MIT. She was primarily concerned with the trihalomethane (THM) production, due to the dual chlorination steps employed by the GOW system (Lantagne, 2001).

THMs are disinfection by-products (DBPs) that are associated with negative human health effects, as expanded upon in section 2.5.4. Lantagne's results indicated that the individual THM concentrations in all of the 17 finished water samples analyzed were below the limits specified by the World Health Organization (WHO). One of the finished water samples contained a combined, total trihalomethane (TTHM) concentration above the WHO specification and the US Environmental Protection Agency (EPA) standard, however. She concluded that the reliability of the granular activated carbon was a key component in maintaining low THM concentrations in the effluent water (Lantagne, 2001).

In addition, Nadine van Zyl submitted her thesis at MIT titled *Sodium Hypochlorite Generation for Household Water Disinfection in Haiti* in May of 2001. Van Zyl investigated alternatives to the imported commercial bleach that was previously used for disinfection in the GOW systems. A new solution was needed due to the high costs, short shelf life, and limited supply of the commercial bleach. She wanted to target a source

within Haiti so that the units would not need to rely on imported goods, and so that the Haitians could be more self-sufficient. Van Zyl conducted a weighted factor comparison, concluding that Excelltec's SANILEC-6 hypochlorite generator would be the best option. This generator would be piloted in Dumay, where Gift of Water, Inc. had the largest and longest presence (Van Zyl, 2001).

Finally, in 2002, Michael Joseph Borucke submitted his thesis at MIT about the *Filtration of Giardia cysts from Haitian Drinking Water*. Borucke investigated the effectiveness of the GOW systems in removing *Giardia lamblia* and *Cryptosporidium parvum*, possible protozoa that could occupy the water sources in Haiti. To do this, Borucke created a bench-scale version of the GOW system and ran water spiked with microspheres of comparable sizes to these protozoa through the units (Borucke, 2002). He ran this test at two different pH conditions because the charge of both the target and the collector particles, and therefore the forces between the two, change with pH, affecting the collection efficiency in the filters (Ongerth & Pecoraro, 1996). His bench-scale model included a 5 μm string filter that was about $1/30^{th}$ the length of the string filter in the GOW system. The GAC cartridge was 8 cm long, 1.5 cm in diameter, and contained 5.51 g of GAC, whereas the GAC cartridge in the GOW system is 21 cm long, 4.8 cm in diameter, and contains 220 g of GAC. His tests concluded that the bench-scale string filter removal efficiency was approximately 30% for a pH value of 8.5 and 0% for a pH value of 7, whereas the full-scale string filter removal efficiency was 20% for both pH values. Furthermore, the bench-scale GAC removal efficiency was approximately 40% for a pH value of 8.5 and 50% for a pH value of 7. He recommended that to

improve upon the removal of these protozoa, the string filter needed to be switched from a 5 μm pore size opening to a 1 μm pore size opening (Borucke, 2002).

2.3 Other Potable Water Solutions in Developing Countries

Household, point-of-use water treatment options have been researched for many years to provide people in developing countries with access to improved drinking water sources. There are many nonprofit organizations, universities, and other facilities that have dedicated their time and money to this problem, and many alternatives have been implemented across the globe thus far. Some of these options include household chlorination, ceramic filtration, slow sand filtration, solar disinfection, flocculant/disinfectant powder, and boiling. According to the Centers for Disease Control and Prevention (CDC), "The most appropriate option for a community depends on existing water and sanitation conditions, water quality, implementation feasibility, availability of technology, and other local conditions" (CDC, 2012).

An example of a household scale chlorination treatment option is the Safe Water System (SWS), developed by the CDC and the Pan American Health Organization (PAHO) in the 1990s. The SWS is a solution of dilute sodium hypochlorite, or chlorine bleach that can disinfect the water from most bacteria and viruses that may be present. This disinfection method has been proven to reduce diarrheal diseases from 22-84% in several random trials. This system is user friendly; users must pour one capful of bleach for clear water, or two capfuls of bleach for visually turbid water, into a standard container, shake the container, and then wait 30 minutes before use. Turbidity lowers the efficacy of disinfectants because the suspended particles in the water can hide the pathogens.

According to the CDC, however, this process is effective in water up to 100 NTU (Alekal, 2005). This system is inexpensive, costing roughly US $0.10 for a bottle of solution that can treat 1,000 liters of water. A possible drawback of this disinfection method is that it is not likely to be effective in removing chlorine-resistant protozoa, such as *Giardia* or *Cryptosporidium*. Furthermore, the effluent water may taste and smell like chlorine, and the water may contain DBPs that will affect the users over time. This treatment option is best suited for water sources with low turbidity, since a physical separation process for the suspended particles is not included. The SWS has been implemented in over 30 countries worldwide, and has grown in popularity through time (CDC, 2012).

An example of a household scale flocculation/disinfection treatment option is the PUR Purifier of Water system, developed by Proctor and Gamble and the CDC. This system consists of a packet of ferric sulfate, which is first stirred into 10 liters of water before allowing the suspended particles to settle to the bottom. Then, the water is strained through a cotton cloth into a second bucket and allowed to sit for 20 minutes after the addition of the second packet, containing calcium hypochlorite. This system employs both the physical separation and the disinfection processes for a multiple barrier approach to clean drinking water. In concept, this system allows suspended particles and protozoa to be removed, with remaining microorganisms being inactivated by chlorine to produce safe drinking water. This system has been proven to reduce diarrheal disease from 16-90% in users, and has been implemented in 23 countries. The system costs about US $0.10, or roughly US $0.01 per liter of treated water (CDC, 2012).

An example of a household solar disinfection treatment unit is SODIS, which was developed by the Swiss Federal Institute for Environmental Science and Technology in 1991. With this system, any plastic soda bottle 0.2 to 2.0 liters in size is filled with water containing low turbidity, shaken for oxygenation, and placed in the sun for six hours to two days, depending on the weather. This process combines "UV-induced DNA alteration, thermal inactivation, and photo-oxidative destruction to inactivate disease-causing organisms" (CDC, 2012). This system is simple, inexpensive, and has been proven to reduce diarrheal disease in a range of 9-86% of users. The water, however, must be pretreated with filtration or flocculation if it contains a turbidity higher than 30 NTU (Wegelin, Canonica, Mechsner, Fleischmann, Pesaro, & Metzler, 1994). Also, only a limited amount of water can be treated at once, and the process is slow because it is conducted as a batch process. This system has been implemented in about 28 countries worldwide (CDC, 2012).

Ceramic filters are broadly implemented throughout developing countries to produce a higher quality drinking water, as well. Potters for Peace (PFP), a non-governmental organization (NGO) out of both the US and Nicaragua, has designed a version of these filters that have been implemented in over 20 countries (CDC, 2012). This filter consists of a ceramic pot comprised of a mix of terra-cotta clay and saw dust. The filters are fired at 887^{o}C and then coated with 3.2% colloidal silver, which aids in bacterial disinfection (Lantagne, 2001). After production, the ceramic filters are placed inside a water storage receptacle such as a plastic bucket. Water is poured into the ceramic pot and allowed to filter through, into the storage receptacle before use. These systems are simple to use and

inexpensive to purchase, selling at a cost of US $7.50 to US $30, depending on the source of the filter. The systems must be cleaned regularly, and the flow rate through these filters is relatively low, averaging from one to three liters per hour if the water is fairly free from turbidity (CDC, 2012). These filters are effective at removing bacteria in the water due to the colloidal silver lining, as well as protozoa in water due to the small pore size in the ceramic material. These filters are not as effective against viruses, however, because most viruses are smaller than the pore size openings of the filters and the colloidal silver is not a strong enough disinfectant for their inactivation (Lantagne, 2001). Diarrheal disease has been reduced in 60-70% of users with the PFP design (CDC, 2012).

Another very common household water treatment system is a slow sand filter. The BioSand Filter, created by the NGO, Samaritan's Purse, is one of the most commonly implemented designs, with roughly 116,000 installations in 24 countries worldwide. Their design consists of a square plastic container approximately 0.9 meters tall and 0.3 meters wide, filled with a small layer of gravel and topped by a small layer of coarse sand and a deeper layer of fine sand. The water level is maintained 5-6 cm above the top of the sand layer, and a diffuser plate is included above that water level so that the added water does not disturb the top layer of the sand. After time, a biological layer, called a schmutzdecke, is established within the top few centimeters of sand, which aids in the inactivation of bacteria and the degradation of organic matter in the water. A reduction on 99.98% of protozoa, 99% of bacteria, and 80-98% of *E. coli* have been reported in the effluent water for the slow sand filter designs studied. Furthermore, diarrheal disease has been reduced by 44-47% in those slow sand filter designs. The Samaritan's Purse BSF

has a higher flow rate than some other filtration units, averaging about 0.6 liters per minute, and they are simple to use. These filters tend to remove most suspended solids from water, and can be produced locally with sand and gravel. They must be cleaned occasionally to prevent clogging, which involves the agitation of the top layer of sand. Slow sand filters range from US $15 to US $60 to implement, but most of this cost is normally covered by donations, and the filters last about ten years (CDC, 2012).

Finally, some developing areas boil their water to inactivate microbial pathogens. This method is one of the oldest and most common. The WHO recommends the water be heated until it reaches boiling point of 100^{o}C (212^{o}F), and the CDC recommends that the water is allowed to boil for at least one minute before usage. This method is obviously recommended in areas with access to a fuel supply for boiling and with a safe storage area to prevent recontamination (CDC). This option is rather unsustainable over time because it requires a large amount of fuel to boil the water required for consumption. In developing countries, the fuel source mainly comes from biomass, such as wood or agricultural waste. In many areas, such as Haiti, the land cannot environmentally support this demand because of deforestation. Furthermore, the daily fuel costs can be unaffordable for many (Gagdil, 2008).

2.4 Business Models for Application in Developing Countries

Water enterprises need to establish sound/strong business models before they can begin their work in developing countries. These models may be more complicated than for other business ventures, since the direct consumers of the product do not usually have the means to pay for the costs of the enterprise, let alone the production cost of the actual

product. For this reason, a water enterprise must ensure financial stability in order to sustainably maintain business practices, without depending on the direct client. Funding for these enterprises often comes from the government, investors, donors, or NGOs (Brown et al.).

Most water enterprises are only concerned with covering the cost of production and distribution of the water systems. It is also common that water enterprises hire advisory services in the areas their systems are implemented to ensure that these areas can be self-sufficient and that the systems are maintained over time. Water projects in developing countries are generally unsustainable due to a lack of ability to maintain the systems. Therefore, a proper business model must include a plan to replace all parts of their systems when necessary (Brown et al.).

Any fees obtained from the clients are usually used for developmental programs, or other ways to benefit the local community. If an investor funds a water enterprise, one option for the enterprise is to return that money to the investors over time with any profits made from their processes. If the enterprise can collect enough money to commercialize the water systems, they can expand to help more people (Brown, et al.).

Another important aspect of a proper business model is education for clean water habits in developing areas. Many inhabitants of underdeveloped areas are unaware of the possible contaminants in their visually clear water sources. Most people are only motivated to make a change if they know a problem exists. For example, people will buy chlorine to disinfect their water only after flood events, when they know the water can become contaminated. Therefore, proper business models should incorporate training

sessions to educate the potential users about why their current practices are unsafe, and how the water system could drastically improve their quality of life. It is important that the culture of the community is understood before these training sessions are held, however, in order to reach out to them in the most beneficial way. Follow-up is also a critical component for a proper business model so the water enterprise can ensure that the message was clear and that the systems are being used correctly (Brown et al.).

2.4.1 Gift of Water's Business Model

GOW has developed an established business model to partner with the communities in Haiti. The first step in that model involves financing the water program. To accomplish this step, a non-profit organization with an established presence in a Haitian community agrees to sponsor a water program in that community. This involves purchasing the systems and the replacement parts, as well as employing the technicians. The next step involves manufacturing and delivering the systems, done by GOW in the US. Next, the sponsoring organization works with community leaders, such as a parish priest or a clinic director, to decide which households will receive the systems. Finally, GOW sends a trained county liaison to the community to establish the program, to distribute the systems and to train a community technician to manage the program locally. The community technician is trained to make household visits to provide maintenance, replacement parts, chlorine tablets, and ongoing training. The distribution portion of the GOW business model was observed in the Belladere, Croix Fer and Dos Celle communities in Haiti during the week of June 10th, as shown in Figure 7.

Figure 7: GOW filter distribution session in Dos Celle.

GOW is active in their local Indiana community, and the organization often holds fundraisers to support their practices. The water treatment systems themselves cost about US $25 to manufacture, but the Haitians are charged US $1.25 per unit. This money is given to the local priests, who buy new chlorine tablets to distribute to the clients after they run out. A non-zero cost is applied to the systems so that the Haitians take some ownership of them, rather than viewing them as a direct giveaway. The small cost gives the filters more value and therefore more importance to the users.

Another important aspect to the GOW business model is proper education for the users. While in Haiti, the group held several training sessions for the users of the water filters. The main message of these training sessions was, “Dlo Kle pas dlo bon,” or, “Clear water is not clean water.” The GOW staff members informed the users about harmful bacteria that could be present in the water as well as the possible causes of contamination. They also discussed possible sicknesses that could stem from drinking contaminated water. To

bring the message home, community members were asked how many people they knew had died from cholera, or other waterborne diseases. All of them knew of cases such as these. The training session also discussed the poverty cycle and how drinking unsafe water could negatively impact their entire lives. The GOW representatives also informed the users about the multiple barrier approach to clean drinking water. They explained how each step in the GOW treatment process will improve the final effluent water quality and how drinking water from the GOW systems will improve their lives. Finally, they demonstrated the treatment process, adding a lot of dirt and sticks into the influent water for effect. After the water came out clear and clean, cups were passed out, and everyone tasted the water to prove that the effluent water was safe for consumption, as shown in Figure 8. The training sessions were interactive so that all the community members could participate. The educational approach targeted the specific culture of the community to get the message across effectively.

Figure 8: Dos Celle community members testing effluent water from the GOW system during the training session.

2.5 Chlorine Chemistry

Chlorine is commonly used for water disinfection across the globe. Chlorine participates in a wide range of reactions with organic and inorganic compounds in water. It also reacts with constituents of microorganisms, often resulting in their death or inactivation. It is important to understand the different techniques for chlorine disinfection, as well as the chemistry behind the process so that the proper method can be used in each water treatment scenario.

2.5.1 Free Chlorine

When chlorine gas is added to water, it reacts rapidly to form hydrochloric acid (HCl) and hypochlorous acid (HOCl), as shown below:

$$Cl_{2(g)} + H_2O \rightarrow HOCl + HCl$$

Hypochlorous acid is a weak acid, and it dissociates to form the hypochlorite ion (OCl^-). This reversible reaction reaches equilibrium rapidly.

$$HOCl \leftrightarrow H^+ + OCl^-$$

The pK_a for this reaction is 7.6 at 20°C, so HOCl primarily exists at a pH below 7.6, and OCl^- primarily exists at a pH greater than 7.6, as shown in Figure 9.

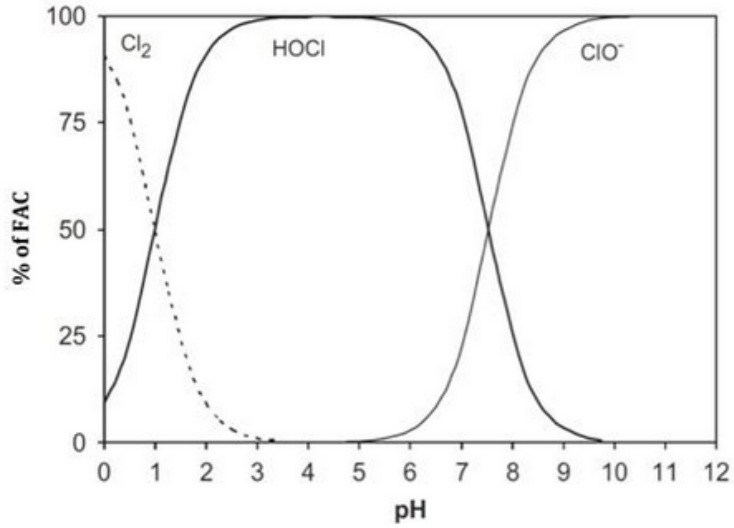

Figure 9: Disassociation of free chlorine (Spahl, 2012).

Free chlorine is defined as the sum of the concentrations of Cl_2, HOCl, and OCl^-:

$$C_{T,Cl} = [Cl_2]+[HOCl]+[OCl^-]$$

HOCl and OCl^- are both strong disinfectants. HOCl is slightly more effective than OCl^-, however. In part, this is because HOCl is a neutral compound, so it can penetrate the negatively charged surfaces of bacteria, as well as the negatively charged suspended particles containing pathogens much more easily than OCl^-. It is also a stronger oxidant than OCl^- (American Water Works Association, 2006).

2.5.2 Inorganic Combined Chlorine

Inorganic combined chlorine, or chloramines, consists of monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine (NCl_3). These substances are commonly used for disinfection in drinking water and are formed when chlorine and ammonia are present in water. The residual provided by inorganic chloramines tends to be relatively stable, and they tend to form fewer disinfection by-products than free chlorine, but they are weaker disinfectants and oxidants. The following substitution reactions lead to NH_2Cl, $NHCl_2$, and NCl_3 production, respectively:

$$HOCl + NH_3 \leftrightarrow NH_2Cl + H_2O$$

$$HOCl + NH_2Cl \leftrightarrow NHCl_2 + H_2O$$

$$HOCl + NHCl_2 \leftrightarrow NCl_3 + H_2O$$

In addition, disproportionation of monochloramine yields dichloramine. Anything that can function as a proton donor will catalyze this reaction. No active chlorine is lost in this reaction, but the dichloramine formation leads to several redox reactions (Jafvert & Valentine, 1992).

$$NH_2Cl + NH_2Cl \leftrightarrow NHCl_2 + NH_3$$

The concentrations of NH_2Cl, $NHCl_2$, and NCl_3 present in solution depend on several factors, such as the $Cl:NH_3$ (Cl:N) molar ratio. A schematic of the breakpoint chlorination curve is shown in Figure 9. As shown in zone 1 on Figure 9, at a very low Cl:N ratio, reducing compounds consume all the added chlorine, so no combined chlorine

is created. In zone 2, when Cl:N is less than one, the chlorine reacts with organics and ammonia in the water, and chloramination occurs. Excess NH_3 is present and monochloramine formation is favored in this range. In zone 3, more dichloramine is formed, and the curve begins to flatten out. As more dichloramine is formed in zone 4, the residual chlorine concentration decreases, and the dichloramine begins to decompose. This decomposition occurs very quickly at first, and chloramine residuals are formed in the process. Finally, zone 5 occurs at the breakpoint, or Cl:N≈1.6-1.7. After this point, all ammoniacal compounds have been oxidized. Free chlorine dominates in this region, although it will often be accompanied by NCl_3. Water may be treated past the breakpoint so that all the chlorine demand can be satisfied while leaving some free chlorine residual in the water to prevent recontamination (American Water Works Association, 2006).

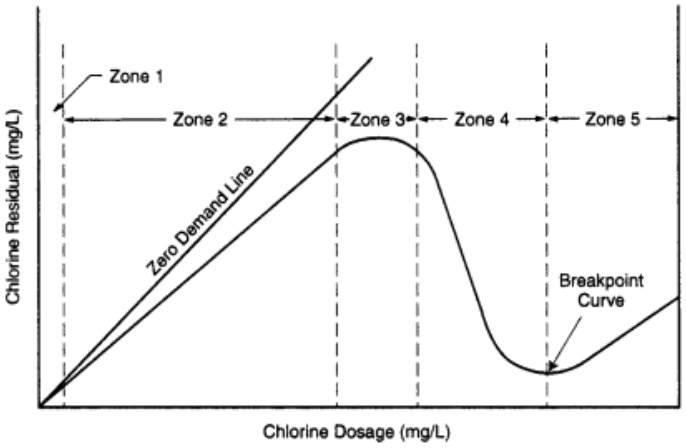

Figure 10: Breakpoint chlorination curve (American Water Works Association, 2006).

The following four equations summarize the redox reactions that dominate under chloramination conditions, or in zone 2. These reactions are relatively slow, so combined residuals are stable in this region (Jafvert & Valentine, 1992).

$$NHCl_2 + H_2O \rightarrow NOH + 2\ H^+ + 2\ Cl^-$$

$$NHCl_2 + NOH \rightarrow N_2 + HOCl + H^+ + Cl^-$$

$$NOH + NH_2Cl \rightarrow N_2 + H_2O + H^+ + Cl^-$$

$$NH_2Cl + NHCl_2 \rightarrow N_2 + 3\ Cl^- + 3\ H^+$$

The following three equations summarize the redox reactions that dominate in zone 5, after the breakpoint. These redox reactions tend to be rapid (Jafvert & Valentine, 1992).

$$NHCl_2 + H_2O + NCl_3 \rightarrow N_2 + 2\ HOCl + 4\ HCl$$

$$NH_2Cl + H_2O + NCl_3 \rightarrow N_2 + HOCl + 3\ HCl$$

$$NHCl_2 + H_2O + 2\ HOCl \rightarrow NO_3^- + H^+ + 4\ HCl$$

2.5.3 Organic Chloramines

Organic chloramines are formed when free chlorine reacts with organic nitrogen compounds, such as amino acids, in the water. The mechanics of organic chloramine production are summarized below:

$$R\text{-}NH_2 + HOCl \leftrightarrow R\text{-}NHCl + H_2O$$

$$R\text{-}NHCl + HOCl \leftrightarrow R\text{-}NCl_2 + H_2O$$

Where R represents the organic nitrogen compounds in the water. According to a study by Ernest R. Blatchley III and Martina Donnermaier, when ammonia and nitrogen compounds are both present in water, both organic and inorganic chloramines are formed.

The distribution of the two products depends on "the relative affinity of +1 valent chlorine for the inorganic and organic N-compounds, the concentrations of the nitrogenous compounds, and the pH," (Blatchley & Donnermaier, 2003). Organic nitrogen compounds are not desired in solution during chlorination because they exert a high chlorine demand, which interferes with the microbial disinfection processes. Organic chloramines do not aid in disinfection, and they form DBPs. Furthermore, organic chloramines are often mistaken for inorganic chloramines in combined chlorine residual testing, which interferes with these measurements (Blatchley & Donnermaier, 2003).

2.5.4 Disinfection By-Products

Hypochlorous acid (HOCl) and hypobromous acid (HOBr), formed from disinfection processes, can react with organics in water to produce some DBPs, which can be harmful to human health. Trihalomethanes (THMs) are a major concern in water treatment because many THMs are classified as "probable human carcinogens." The mechanics of THM production are summarized in the following reaction:

$$\text{Precursor(s)} + \text{HOX} \rightarrow \text{CHX}_3$$

Where the precursors represent organic matter in the water, X represents Cl or Br, and CHX_3 represents the THM. Some THMs include chloroform ($CHCl_3$), bromodichloromethane ($CHCl_2Br$), dibromochloromethane ($CHClBr_2$), and bromoform ($CHBr_3$). According to the USEPA, long term exposure to total THMs can induce liver, kidney, and central nervous system problems, and can increase the risk of cancer (EPA,

2013). For these reasons, the US EPA regulates the MCL for total THMs in drinking water to be 80 μg/L. The WHO guidelines for the individual THMs in drinking water are shown in Table 1 (CDC).

Table 1: WHO guidelines for THMs in drinking water.

	WHO Guideline Value
Chloroform	200 μg/L
Bromodichloromethane	60 μg/L
Dibromochloromethane	100 μg/L
Bromoform	100 μg/L

Haloacetic acids (HAAs) represent another class of DPBs. The five most common HAAs, referred to as HAA_5, are monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid (American Water Works Association, 2006). According to the US EPA, long-term exposure to HAAs can also increase the risk of cancer. For this reason, the US EPA regulates the MCL for the sum of the concentration of HAA_5 in drinking water to be 60 μg/L (EPA, 2013).

THMs and HAAs are commonly used as indicators for all potentially harmful compounds created during chlorination in water (CDC). Filtration is commonly used to remove either the precursors for DBPs, or the DBPs themselves. Other methods include activated carbon treatment, membrane filtration, and UV irradiation (American Water Works Association, 2006).

2.5.5 Disinfection Kinetics

In 1908, Dr. Harriet Chick proposed that disinfection can be modeled as an elementary, bimolecular reaction, as follows:

$$A+B \rightarrow C$$

where A is the microorganism, B is the disinfectant, and C is the inactivated microorganism. She developed the following equation for the disinfection rate of viable organisms in solution:

$$dN/dt = -kN$$

where: N = concentration of organisms (org/L)

k = rate constant (min^{-1})

t = time (min)

That same year, Herbert Watson proposed that the disinfection rate could be related to the disinfectant concentration, as well. His equation for disinfection is as follows:

$$C^n t = constant$$

where: C = Concentration of disinfectant (mg/L)

n = empirical constant

t = time required to achieve desired inactivation (min)

constant = value for desired percentage of inactivation

Today, a combined equation, or the Chick-Watson model, is commonly used to quantify the disinfection kinetics in terms of both the disinfection concentration and time. This equation is as follows:

$$dN/dt = -\Lambda_{CW}CN$$

where: dN/dt = rate of change of the concentration of viable organisms (org/L/min)

Λ_{CW} = disinfection rate constant (L/mg/min)

The Chick-Watson model can be re-written as follows for application to a well-mixed, batch reactor:

$$\ln(N/N_o) = -\Lambda_{CW}Ct$$

where: N_o = concentration of organisms at time t=0 (org/L).

The disinfectant dose can be defined as Ct, or the concentration of the disinfectant multiplied by the time of disinfection. This model predicts a pseudo-first-order disinfection trend. However, as shown in Figure 11, deviations from first-order behavior are often observed, including a lag in microbial inactivation and tailing. Possible explanations for a lag include the existence of a sub-lethal dose, a requirement that the disinfectant must react with multiple critical sites in an organism, and the existence of repair mechanisms. Possible explanations for tailing include: heterogeneity in organism resistance and particle interference (Crittenden et al., 2012).

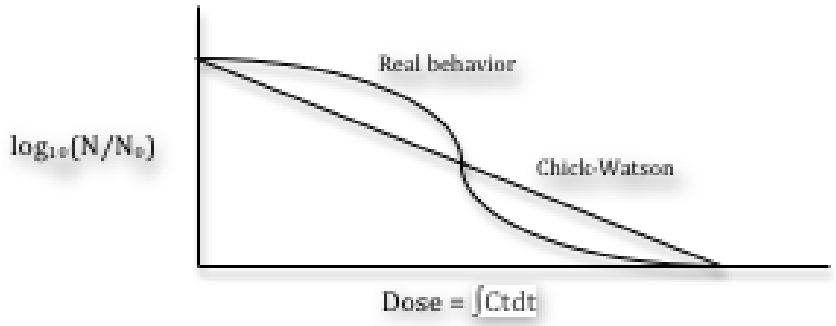

Figure 11: Deviations from Chick-Watson kinetics.

2.6 Filtration Theory

Filtration is the separation of particles from a fluid by passing a fluid suspension through one or more collecting media. Filtration has been used in water treatment for thousands of years (Crittenden et al., 2012). Filtration is used to remove solid particles from water, thereby improving the clarity and the turbidity of water. Filtration will also remove some microorganisms, thereby easing the disinfection component requirements of a system. Physical separation, such as by filtration, is critical because some microorganisms, such as *Giardia lamblia* and *Cryptosporidium parvum*, are resistant to chlorine. As described previously, filtration can help to prevent waterborne disease outbreaks. For example, there was a massive cholera outbreak in Hamburg, Germany that caused over 7,500 deaths in 1892. Although Altona, a neighboring city, drew from the same water source, none of the residents were infected, in part because they used slow sand filtration before consuming the contaminated water (Huisman & Wood, 1974).

2.6.1 Transport Mechanisms

There are three transport mechanisms for collection of particles on filter medium. Water is assumed to follow streamlines around the filter medium. One transport mechanism by which particles in the water can collect on the filter medium is interception, which occurs when the streamlines are so close to the filter media that the particles collide with the collecting medium and become stuck. As the particle sizes get bigger, so does the collection efficiency through interception. The transport efficiency equation for interception is shown below (Crittenden et al., 2012).

$$\eta_I = \frac{3}{2}\left(\frac{d_p}{d_c}\right)^2$$

where: η_I = interception transport efficiency

d_p = particle diameter (m)

d_m = approximate medium diameter (m)

Sedimentation, a second transport mechanism, is when particles with a greater density than water deviate from the streamline and collide with the filter medium. The collection efficiency for sedimentation is represented by the ratio of the terminal settling velocity of the particle to the approach velocity of the fluid (Crittenden et al., 2012).

$$\eta_S = \frac{V_t}{V_0} = \frac{(\rho_p - \rho) g d_p^2}{18 \mu V_0}$$

where: η_S = sedimentation transport efficiency

ρ_p = particle density (kg/m^3)

ρ = water density (kg/m^3)

g = gravitational acceleration (m/s^2)

d_m = approximate medium diameter (m)

μ = fluid viscosity (Ns/m^2)

V_0 = approach velocity

Finally, the third transport mechanism is diffusion. This is when particles contact the medium because random, Brownian motion allows the particles to stray from the streamline. The transport efficiency equation for diffusion is shown below (Crittenden et al., 2012).

$$\eta_D = 0.9 \left(\frac{kT}{\mu d_p d_m V_0} \right)^{2/3}$$

Where: η_D = diffusion transport efficiency

k = boltzmann's constant = $1.38*10^{-23}$ m^2kg/s^2K

T = temperature (K)

The total collection efficiency in a filter is equal to the sum of the three transport mechanisms ($\eta_T = \eta_I + \eta_S + \eta_D$). Figure 12 displays the total transport efficiency as a function of particle size for a granular (sand) media, with an effective size of 0.5 mm. The diffusion transport mechanism dominates on the first half of this curve, and after the minimum point, interception and sedimentation dominate. The minimum total contact efficiency for this model occurs at a particle diameter of 2 μm. As displayed in the figure, viruses are predominately smaller than 1 μm, bacteria are normally around 1 μm, and protozoa are greater than 1 μm in size (Crittenden et al., 2012).

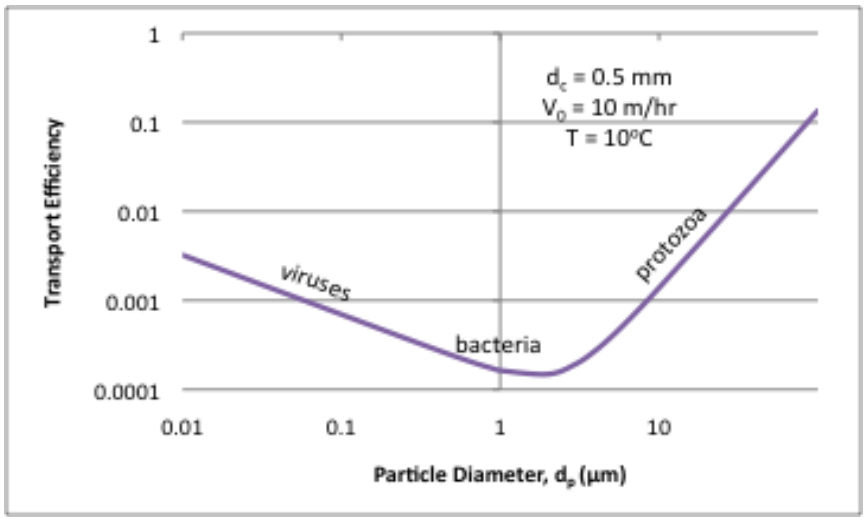

Figure 12: Total contact efficiency as a function of particle size.

2.6.2 Filter Design

Grain shape is an important aspect of filter design. The grain shape affects the grain size distributions, how the grains pack together in the filter bed, and the hydraulics through the filter. A fairly uniform grain size and a spherical grain shape are ideal for water filtration because these conditions create smaller voids and remove more material than

the alternative (GE, 2013). Filter porosity is also an important aspect in filter design. Filter beds generally consist of 40-60% porosity, depending on the media used and how they are packed together. Filters with higher porosity values are more efficient because there is more void space to collect more particles. Another important aspect of filtration design is the specific surface area of the granular bed. If the media has a higher surface area, there will be a greater chance for the particles to attach to that media and not flow through with the effluent water (Crittenden et al., 2012). The following equation models the particle removal in a filter:

$$\frac{N}{N_0} = \exp\left[\frac{-\psi(1-\varepsilon)}{d_m}\eta_T x\right]$$

where: N = concentration of particles

N_0 = initial concentration of particles

x = distance into filter bed (m)

ψ = shape factor

ε = media porosity = pore volume/bed volume

2.6.3 Basic Filter Types

There are two basic filter types: a surface filter and a depth filter. On a surface filter, particles accumulate on the upstream side of the media, and particle separation occurs from size exclusion. Slow sand filters are a common type of surface filter. Slow sand filters consist of a container encasing fine sand, with an average flow rate of about 0.1 to

0.4 m^3/hr per square meter of surface area (Huisman & Wood, 1974). The schmutzdecke layer, as defined in section 2.3, forms on the very top of the sand after only a couple days of use. This layer, consisting mainly of organic matter, iron, manganese and silica, aids the filters in removing finer particles and some soluble organics. After slow sand filters begin to clog, this layer can be scraped off or disturbed to initiate adequate flow through the system, but these filters produce the best effluent water quality with a mature schmutzdecke layer. Slow sand filters are convenient in areas with more space and with less water needs because although they produce less water, they produce a very high quality effluent. Furthermore, they are fairly inexpensive to produce if the materials are all locally available, and they require very little maintenance (Crittenden et al., 2012).

In a depth filter, particle deposition is attributable to the physical and chemical interactions described above (*i.e.*, collection mechanisms), and particle penetration is possible through the entire filter bed. Rapid sand filtration is a commonly used depth filter today due to the faster rate of water production. Because rapid sand filters use the entire filter bed depth for filtration instead of the top layer alone, a higher output of water is produced with a smaller surface area (Crittenden et al., 2012). The media used in a rapid sand filter is often uniform, mainly consisting of sand or anthracite. Multi-media filters are also common in rapid sand filtration. Multi-media filters contain multiple layers of anthracite, sand, garnet, and/or magnetite (GE, 2013). Coagulation is often used as pretreatment for rapid sand filters to destabilize the particles so that the negative charge on the particles does not repel the negatively charged sand media. During filtration, particles collect through the depth of the filter. Then, the accumulated particles

are backwashed out of the system, and the filtered water is collected for disposal. Rapid sand filters must be backwashed regularly (*e.g.*, daily), and are generally more expensive to maintain due to energy costs (Crittenden et al., 2012).

2.6.4 Protozoa Removal

Parasitic protozoa, such as *Cryptosporidium parvum* and *Giardia lamblia*, are both common in users of drinking water that has been contaminated by human or animal excrement. Surface water sources are more vulnerable to this contamination. The spread of these protozoa are more common in developing countries, where proper drinking water sources are not available and where proper hygiene and sanitation practices are not followed (WHO). These protozoa are, therefore, a big concern for the drinking water in Haiti. In a study of 540 Haitians infected with the human immunodeficiency virus conducted from 1990-1993, 3% had been infected by *Giardia* and 30% had been infected by *Cryptosporidium* (Pape et al., 1994). Consuming water or food contaminated with *Cryptosporidium* or *Giardia* can lead to diarrhea, gas, greasy stool, abdominal cramps, upset stomach, nausea, and dehydration (CDC, 2012). These protozoa are both protected by a hard outer shell, making them resistant to chlorine-based disinfection. Therefore, physical separation is a common strategy for treatment of surface water when chlorine is used as a disinfectant. *Cryptosporidium* oocysts typically range from 3 to 7 μm in size, whereas the *Giardia* cyst typically ranges from 7 to 15 μm, so any filtration system with a nominal pore size opening smaller than 3 μm should successfully remove these protozoa (Allgeier et al., 2003).

2.7 Granular Activated Carbon

GAC is used in water treatment to remove the soluble organic and inorganic compounds from water, as well as for dechlorination (Crittenden et al., 2012). Some examples of organic compounds that are removed with GAC are DBPs, natural organic matter, metals, synthetic organic chemicals, and radionuclides (Jurenka, 2010). These compounds can be naturally found in the water, or they could have been formed during biological or chemical treatment upstream. These compounds are removed through their adsorption to the outer and inner surfaces of the carbon particles. Adsorption is the interphase accumulation of materials at the solid:fluid interface (Crittenden et al., 2012).

GAC systems are generally comprised of a column filled with GAC. GAC is produced from coal, wood, nutshells, and other carbon rich materials. These materials are heated anaerobically to produce a material with an extremely high carbon (Crittenden et al., 2012). GAC is unique because it has an extremely large surface area, typically ranging between 650 and 1000 m^2 per gram of material, making the adsorption capacity much greater (Jurenka, 2010). The total contaminant removal capacity of GAC will depend on the adsorption isotherm for that carbon source, as well as the column operating characteristics. The adsorption process takes place in the mass transfer zone, or the required bed depth for complete absorbance. The empty bed contact time (EBCT) is the volume of the empty bed divided by the flow rate of water through the carbon filter. The average EBCT in a GAC filter is between 5 and 60 minutes. Particle size and hardness are important aspects of GAC design. Harder carbons are more durable and less susceptible to damage during handling and construction. As for particle size, it is

important that the particles are not too small; the average particle diameter ranges from 0.6 to 2.36 mm. The bed porosity is also an important aspect of a GAC filter, with the average porosity ranging from about 20-70% (Crittenden et al., 2012).

Water is generally filtered by gravity through GAC systems, and there is normally a screen, or an underdrain system, so that the GAC does not leave the system with the effluent water. These systems are generally designed with approximately 50% freeboard to leave room for expansion during backwashing. GAC systems are typically installed after filtration and disinfection to remove large amounts of suspended solids and bacteria beforehand. Typically, the water is also disinfected afterwards to prevent biological growth (EPA, 2000).

CHAPTER 3. METHODS AND MATERIALS

3.1 GOW System Components

The Gift of Water system consists of two five gallon buckets connected by a check valve, a string filter (5 μm or 1 μm), a cylindrical vessel filled with GAC, and a pour spout for the product water, as illustrated in Figures 13-15.

Figure 13: Two bucket filtration system.

Figure 14: String-wound filter.

Figure 15: Cartridge filled with GAC.

Water is applied in a batch mode in the GOW system. The daily charge of water (5 gallons, or approximately 20 L) is applied to the first (red) bucket, where it is subjected to prechlorination via addition of sodium dichloroisocyanurate (NaDCC, or $NaCl_2(NCO)_3$), a solid form of free chlorine (mass = 67 mg as Cl_2). NaDCC is a reliable, cost-effective chlorine disinfection alternative (Clasen & Edmondson, 2006). NaDCC reacts with water to form hypochlorite and cyanites:

$$NaCl_2(NCO)_3 + 2\ H_2O \leftrightarrow 2\ HOCl + NaH_2(NCO)_3$$

When applied to a 20 L charge, this yields a free chlorine dose of 3.35 mg/L (as Cl_2). The prechlorinated water is allowed to sit for 30 minutes, at which point the first bucket is connected to the second (grey) bucket, thereby initiating flow through a check-valve. This allows the prechlorinated water to flow first through a string-wound filter and second through the cylindrical cartridge containing GAC. Water then flows into the second bucket, where it is chlorinated again (mass = 17 mg as Cl_2), yielding a secondary chlorine dose of 0.85 mg/L (as Cl_2). For the first round of experiments, tests were run on three systems with 1 μm string filters and three systems with 5 μm string filters, for proper comparison of the two alternatives.

3.2 Sources of Water

The first round of experiments involved collection of raw (untreated) water from a community boat ramp on the Wabash River in West Lafayette, Indiana, as shown in Figure 16. 30 gallons of water were collected and stored in the lab four times a week for eight weeks, the night before testing so the water could be brought up to a higher

temperature to better mimic the conditions in Haiti. During laboratory experiments, 13 total water samples were collected for analysis from several locations: one raw water sample, six intermediate samples (after treatment in the top bucket), and six final effluent samples (after the secondary chlorine dose) from each system.

Figure 16: Water collection location at boat ramp on Wabash River in West Lafayette, Indiana.

For the phage tests, the Milli-Q system in the Food Science Lab at Purdue University was used as the water matrix. The water from this system is Type 1, ultrapure water that is dispensed through a 0.2 μm membrane filter before use, making this water source very clean free from particles that could have altered the test results. Wabash River water was also used in these experiments to observe the phage inactivation in a natural water source.

For the clogging rate experiments, secondary effluent from the West Lafayette Wastewater Treatment Plant was used. This water was characterized by relatively low suspended solids concentration, apart from the inevitable algae that grows in the summer season.

Furthermore, while in Haiti, water samples were collected from several sources that were used by the three communities that were visited during the week. Turbidity measurements and *E. coli* concentration data were collected from each water source. These tests provided information regarding water treatment needs in these communities, and it also allowed for comparison with the water sources used in laboratory experiments.

3.3 Flow Rate

The flow rate through the string filters in each unit was measured every day as a means of assessing the effects of the string filters on finished water production rates. To conduct these measurements, a screw was used to push the check valve into the open position, and water was allowed to flow into a 100 mL graduated cylinder for roughly 10 seconds (recorded by a stop watch). The volume and the time of measurement were both recorded, thereby allowing calculation of flow rate. The setup for the flow rate testing process is shown in Figure 17.

Figure 17: Flow rate testing setup.

3.4 *E. Coli*

A membrane filtration method (EPA Method 1101.3) was used for the quantification of viable *Escherichia coli* (*E. coli*) in raw, intermediate, and finished water samples during each day of experimentation. *E. coli* are commonly used as an indicator of fecal contamination (EPA, 2000). A picture of the membrane filtration setup is shown in Figure 18.

Figure 18: Membrane filtration testing setup.

3.5 Turbidity

Turbidity is a measure of the ability of a sample to scatter light. Light scattering in water samples is caused by colloidal particles. As such, turbidity represents a surrogate measurement of colloidal content in water samples.

For each day of testing, turbidity was measured in each of the 13 water samples using a portable turbidimeter, as shown in Figure 19. For reference, the Surface Water Treatment Rule of the US EPA requires that systems based on direct filtration have turbidity less

than 1 NTU in 100% of samples, and less than 0.3 NTU in 95% of samples. Systems that involve something other than direct filtration must produce water that has turbidity less than 5 NTU (EPA, 2004); (EPA, 2010). The WHO has established recommended turbidity limits that are similar to the limits that are imposed by the US EPA (WHO, 2006).

Figure 19: Portable Turbidimeter.

3.6 DPD/KI Colorimetric Method

Free and total residual chlorine were measured in each of the 12 treated samples (six intermediate samples and six final effluent samples) on each day of experimentation. The raw water sample was not tested for free or total residual chlorine. The DPD/KI colorimetric method was used for these measurements. DPD reacts with free chlorine to yield Würster Dye, a magenta-colored compound which increases in intensity with increasing free chlorine concentration. Addition of KI allows DPD to react with combined chlorine to yield the same colorimetric signal. As such, the DPD signal is interpreted as free chlorine, whereas the DPD/KI signal is used as a measure of total residual chlorine (i.e., free chlorine + combined chlorine). Free chlorine measurements

by this method tend to be largely free of interference; however, the DPD/KI (combined chlorine) signal is subject to interference by a number of compounds, including organic chloramines.

DPD and DPD/KI measurements were conducted using pre-packaged reagent tablets from Palintest Kits. Specifically, Palintest method 7 was used with a colorimeter that was programmed to conduct measurements at a wavelength of 515 nm, using DI water as a blank. Then, 10 mL of the water sample was poured into a test tube, and a Palintest 1 tablet was added. The tablet was crushed and stirred until dissolved, after which the sample was immediately inserted into the colorimeter for reading. Next, the test tube was removed, and a Palintest tablet 3 was added. Again, the tablet was crushed and stirred until dissolved. For this second measurement, the solution was allowed to react for two minutes (this time is needed for color development by reaction with combined chlorine) before the concentration was recorded on the colorimeter. The Palintest colorimeter used for this experiment is shown in Figure 20. All measurements were conducted on water samples that had been subjected to the full chlorine dose in each bucket.

Figure 20: DPD/KI Colorimeter.

3.7 Membrane Introduction Mass Spectrometry

The concentrations of volatile disinfection by-products in the water samples were measured once per week using membrane introduction mass spectrometry (MIMS). In MIMS, water samples are pumped through a tubular hydrophobic membrane. Water is rejected by the membrane, but volatile compounds are able to diffuse through the membrane and then swept into a mass spectrometer for detection. The abundance of ions at pre-defined mass/charge (m/z) ratios is then compared with calibration curves for each of the DBPs of concern to allow quantification. The mass spectrometer is shown in Figure 21.

MIMS is applied regularly at Purdue University for identification and quantification of as many as 11 volatile DBPs in chlorinated water samples. To account for instrument drift, it was necessary to evaluate a standard solution on each day of experimentation. Previous work has demonstrated that chloroform works well as a standard for these measurements, because of its chemical stability and relative volatility (Weaver et al., 2009). The chloroform standard was therefore prepared each day the MIMS unit was used so that the calibration curves could be prepared for data analysis.

Figure 21: Membrane Introduction Mass Spectrometer.

3.8 UV Absorbance 254

Chlorine reacts with a wide range of organic compounds to yield DBPs. In natural water samples, it is not practical to identify or quantify the entire range of organic compounds that could function as DBP precursors. Therefore, index tests are often used to characterize the burden of DBP precursor material in a water sample. Among these index tests is UV absorbance. The justification for using UV absorbance as a surrogate for DBP precursors is that many of the compounds that are known to react with chlorine contain unsaturated bonds, or functional groups that absorb strongly at characteristic wavelengths. For example, most unsaturated bonds (e.g., C=C or aromatic rings) will absorb strongly at 254 nm; absorbance at this wavelength is strongly related to the concentration of compounds that contain these groups. As such, measurements of absorbance at wavelengths that are characteristic of reactive compounds or functional groups can be used as an index parameter for DBP formation potential.

For all water samples collected in this research, absorbance scans have been conducted for the wavelength range of 400 to 200 nm. All absorbance scans were conducted on a Cary 300 UV/visible scanning spectrophotometer, using DI water as the blank. For purposes of this document, only data at 254 nm are presented.

3.9 Clogging Rate

To test the clogging rate in the filters, three buckets containing 1 μm string filters and three buckets containing 5 μm string filters were set up at the upstream end of the chlorine contact chamber (secondary effluent, prior to chlorination) at the West Lafayette

WWTP. A wooden platform was built to span the contact chamber entrance. Then, six grey bucket lids, spanning the entire opening, were attached to the boards with duct tape. The check valve was attached to the grey lid, and the red buckets, including their respective string filters, were placed on top of their corresponding grey lids. A weir was constructed by cutting a notch across the top edge of each bucket, thereby fixing the free surface elevation in each bucket. This allowed a constant head to be applied to each filter, with the excess flow simply passing over the weir. A hole was drilled in the lid of each red bucket to receive a length of garden hose. A submersible pump with a hose, a two-way splitter, two four-way splitters, and six shorter hose sections were used to pump the water from the contact chamber into each of the buckets. Furthermore, an additional bucket was used to place the flow splitters on the same horizontal plane as the top of the red buckets so that flow could be easily initiated and uniformly distributed among the six buckets. During the course of these experiments, a constant flow rate was applied to the manifold system that delivered water to the six units to expedite the clogging process. The final setup is shown in Figure 22. Figure 23 also illustrates a rear view of the setup, with the bucket overflow spilling back into the contact chamber.

Flow rate measurements were conducted by collecting a volume of water from the check valve using a graduated cylinder and a stopwatch. A turbidimeter was used to measure the turbidity. Both the flow rate and turbidity were measured daily.

Figure 22: Clogging rate experimental setup at the West Lafayette WWTP.

Figure 23: Rear view of the filter setup at the WWTP.

3.10 Inactivation Assays

Bacteriophage (phage) are commonly used as surrogates for human viruses in tests of physical or chemical disinfection. Viruses are microorganisms consisting of either DNA or RNA that are surrounded by a capsid, or a protein shell, and they can only survive when they invade living cells, such as bacteria (Mayer, 2010). Two types of phage were used; ΦS1 and T4. ΦS1 is a virus that infects the bacteria *Pseudomonas fluorescens*. This phage consists of a linear, double stranded DNA, is about 60 nm wide and 30 nm long, and belongs to the family, *Podoviridae* (Sillankorva et al., 2012). T4, on the other hand, is a virus that infects *Escherichia coli*. This phage also consists of a double stranded DNA, is about 90 nm wide and 200 nm long, and belongs to the family, *Myoviridae* (Miller et al., 2003). For this experiment, the ΦS1 was grown up in the lab, and the final bacteriophage contained a titer of $3.85*10^{11}$ pfu/mL. The T4 used was already available in the lab and at a titer of $4*10^{10}$ pfu/mL.

Plaque assays were performed to measure the concentration of infectious phage before and after treatment in the GOW system. In plaque assays, host cells (*Pseudomonas fluorescens* and *Escherichia coli* in this case) are infected with the phage, plated in a petri dish with an agar, and then incubated. During the incubation period, infective viruses are able to invade the host cells, which then lyse and spread to the adjacent cells for further viral invasion. This infected area forms a plaque, which can be counted to find the viral concentration in the sample. Three replications for each sample were performed to allow measurement of variability in phage viability, and serial dilutions were done for each replication to ensure that countable numbers of plaques were evident for at least one

dilution. To accomplish this, dilution tubes were filled with 900 µL of sterilized water. The first dilution tube was filled with 1000 µL of the sample, and then 100 µL of that first dilution was added to the second dilution tube, and so on. These dilutions were combined with the bacteria and then plated, as previously described. A vortex mixer was used to ensure adequate mixing throughout the experiments. A schematic of this is shown in Figure 24.

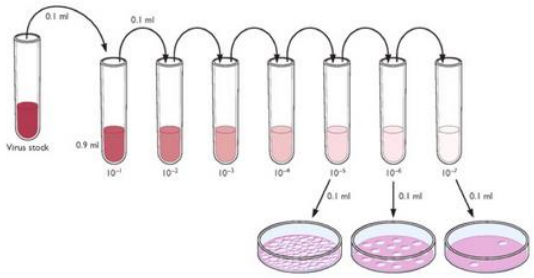

Figure 24: Plaque Assay Schematic (Racaniello, 2009).

Several phage inactivation experiments were conducted for this phase of the project. First, bacteriophage were added to pure, Milli-Q water as a control. One 20-L bucket was filled with Milli-Q Water, 1.0 mL of the ΦS1 phage suspension, and 1.0 mL of the T4 phage suspension. A second 20-L bucket was filled with Milli-Q Water, the first chlorine dose (67 mg Cl_2), 1.0 mL of the ΦS1 phage suspension, and 1.0 mL of the T4 phase suspension. Plaque assays were performed on both of samples, for both the ΦS1 and T4 phage suspensions, after 30 minutes of contact time. 1.87 mg of sodium thiosulfate ($Na_2S_2O_3$) was added to 1.0 L of each sample to inactivate the free chlorine after the contact time so that no further inactivation would occur during the plaque assays. Plaque assays were performed on the plain water samples with each phage suspension, the plain water samples with each phage suspension and 1.87 mg of sodium

thiosulfate, the chlorinated water samples with each phage suspension, and the chlorinated water samples with each phage suspension and 1.87 mg of sodium thiosulfate to prove not only that the free chlorine dose effectively inactivates both phage types, but also that the sodium thiosulfate does not alter the phage properties. The chemistry of the sodium thiosulfate reaction with chlorine is as follows (Tikkanen et al., 2001):

$$Na_2S_2O_3 + 4\ HOCl + H_2O \rightarrow 4\ HCl + 2\ NaHSO_4$$

During the next experiment, Wabash River water was used instead of the Milli-Q water so that the behavior of the bacteriophage in a natural water source could be studied. For this experiment, one 20-L bucket was filled with Wabash River Water, 1.0 mL of the ΦS1 phage suspension, and 1.0 mL of the T4 phage suspension. A second 20-L bucket was filled with Wabash River Water, the first chlorine dose (67 mg Cl_2), 1.0 mL of the ΦS1 phage suspension, and 1.0 mL of the T4 phage suspension. A third 20-L bucket was filled with Wabash River Water, the first chlorine dose (67 mg Cl_2), 1.0 mL of the ΦS1 phage suspension, and 1.0 mL of the T4 phage suspension. This third bucket was poured into the top bucket in the GOW system, where the entire GOW filtration process began. After being subjected to the second chlorine dose (17 mg Cl_2) for another 30 minutes, the sample was taken. Sodium thiosulfate was also used in this experiment to inactivate the chlorine before the plaque assays began. 1.87 mg of sodium thiosulfate was added to 1.0 L water samples from the first two buckets, and 2.34 mg of sodium thiosulfate was added to a 1.0 L water sample from the third bucket effluent to sufficiently dechlorinate the water samples after the allotted chlorine doses. Plaque assays were run on a sample from each bucket, as well as the samples with sodium thiosulfate. The free chlorine residual

throughout the disinfection process was monitored for this experiment, as well, using the DPD/KI colorimetric method.

3.11 Source Water Testing in Haiti

While in Haiti, an opportunity emerged to assist the Gift of Water Team in training sessions, as well as the final distribution of the systems to the chosen households in the Belladere, Croix Fer, and Dos Celle communities. Figure 25 shows a map of Haiti, highlighting the Belladere Community. Croix Fer and Dos Celle are smaller communities in Haiti, so they are not easily found on a map. Dos Celle, was roughly an hour drive Southwest of Belladere, close to the Dominican Republic Border, whereas Croix Fer was about a 30 minute drive East of Belladere.

Figure 25: Map of Haiti with Belladere community highlighted in red.

While in Belladere, Croix Fer, and Dos Celle, water samples were collected for testing from several commonly used water sources. Turbidity was measured in these samples using a portable turbidimeter. Viable *E. coli* were quantified in these water samples using the compartment bag test (Aquagenx, 2013). This test allows for detection of the presence/absence of viable *E. coli* using a chromogenic reagent that is specific to *E. coli*. By applying the test across a range of sample volumes, it is possible to estimate the concentration of viable *E. coli* in the original sample (with a standard deviation) by application of the Most Probable Number (MPN) method. The steps to this test are as follows:

1. Collect 100 mL of a water sample in a sterile sample container. Store this sample out of direct heat or sunlight until analysis.
2. Insert chromogenic culture medium into the sample container. Wait about 15 minutes for the medium to dissolve, swirling the container periodically to allow for mixing.
3. Open the compartment bag, and pour the contents of the sample container into the bag. Adjust the volumes in each compartment until they reach the lines designated on the bag.
4. Seal the compartment bag, and incubate the sample overnight. This can either be done in an incubator or in a room with ambient temperature. If the bag is stored at 35-44^{o}C, the incubation period must be 20-24 hours, whereas the incubation period must be 24-30 hours when stored at 30-35^{o}C, and 40-48 hours when stored at 25-30^{o}C.

5. After the incubation period is complete, the results can be analyzed and recorded. Table 2 Shows the classifications of the results, the color schematic corresponding to each classification, as well as the numerical estimates of the MPN and the confidence intervals for each measurement. The results are analyzed through color gradients in the compartment bag.

Table 2: Water quality rating for Compartment Bag Test (Aquagenx, 2013).

Safety of Results	Color Schematic	MPN/100 mL	Upper 95% Confidence Limit Value/100mL
Unsafe	Red	>100	9435.1
Likely Safe	Yellow to Red	48.3	351.91
Possibly Unsafe	Yellow	13.6	83.06
Possibly Safe	Yellow to Green	4.7	22.75
Likely Safe	Green to Yellow	1.5	7.81
Safe	Green	0	2.87

6. Decontaminate the contents of the bag with a provided chlorine tablet before disposing of the sample. After adding a chlorine tablet, mix well and wait 30 minutes. Then, pour the contents into a sink, toilet, etc (Aquagenx, 2013).

CHAPTER 4. RESULTS AND DISCUSSION

4.1 1 μm String Filter vs. 5 μm String Filter

The following sections summarize the results of the experiments conducted to compare the water quality throughout the GOW filtration process for the two filter types. As previously mentioned, three string filters with a nominal pore size opening of 1 μm and three string filters with a nominal pore size opening of 5 μm were tested in this phase of the experiment. The data points for the respective filter types throughout this section represent the mean measurement taken on each day of experimentation. The detailed measurements, recorded in tabular form, can be found in appendices A through I at the end of the report.

4.1.1 Gage Height and Discharge

For context, it is relevant to understand the conditions of the source water being used for experimentation. This phase of the project conducted from March 12, 2013 to May 15, 2013. Both the gage height and the discharge in the Wabash River fluctuated drastically during this period, which greatly affected the water composition. Figure 26 illustrates the gage height and discharge measurements, obtained from the US Geological Survey (USGS), throughout the time frame of the experiment (USGS, 2013). The detailed measurements throughout the course of the experiment can be found in tabular form in

Appendix A. As one can infer from this graph, the rain events between April 12th and May 7th raised the gage height and the river discharge dramatically. The flood stage of 11 ft, as depicted by the black line, was exceeded during these events. After heavy rain events, river velocities tend to increase due to heavy runoff, as shown by the similar time-course trends in the two data sets (EPA, 2012). Both measurements stayed consistently high until around May 7th, when the rain events slowed and the water levels began to drop below the flood stage.

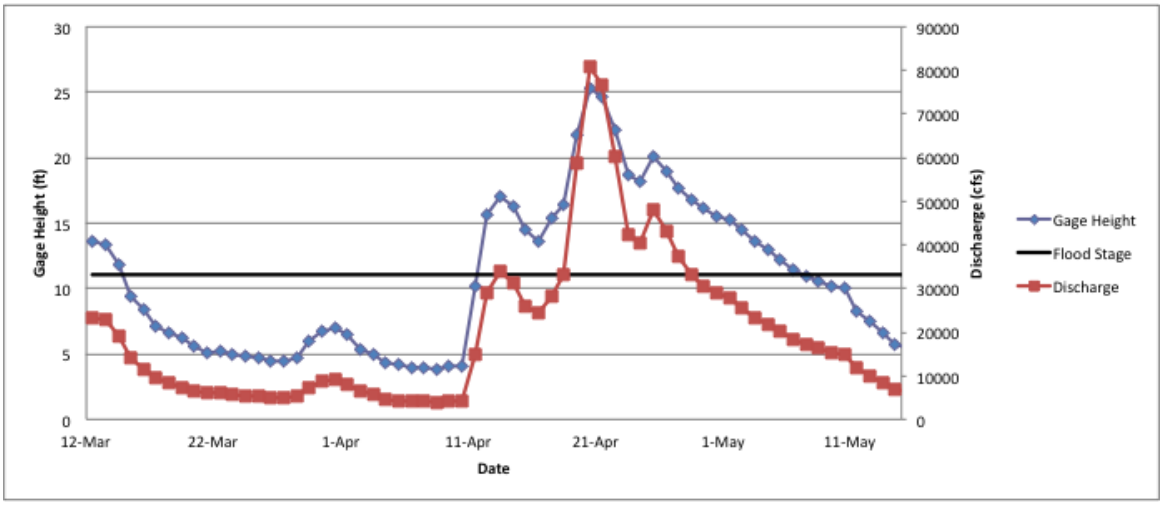

Figure 26: Gage height and discharge data for Wabash River gaging station throughout the course of the experiment (USGS, 2013).

4.1.2 Flow Rate

The results of the flow rate measurements are illustrated in Figure 27. The detailed flow rate measurements throughout the course of the experiment can be found in tabular form in Appendix B. These measurements were taken when the buckets were full, containing 5 gallons of water. Little or no change in flow rate was observed for either filter type during the span of the experiment. This implies that clogging of the filters by colloidal

particles from the source water was not sufficient to cause an obvious change in flow rate during the eight week span. Moreover, the flow rates through the two filter types appear to be essentially identical. To prove the validity of this statement, an independent-samples t-test was performed on the data for each day of experimentation. The results of this t-test are shown in Table 11 in Appendix B. There was a 95% confidence level that the two data sets were indistinguishable, except for on two days of experimentation; March 21st and April 18th. This implies that it is acceptable to assume that the flow rates between the two filters behave fairly identically under full-flow conditions. The error bars for each data point represent the standard deviation between the three filter types of each size. The maximum and minimum standard deviations in the flow rate measurements for the 1 μm filters throughout the course of the experiment were 1.39 mL/s and 0.11 mL/s, respectively. The maximum and minimum standard deviations in the flow rate measurements for the 5 μm filters throughout the course of the experiment were 2.37 mL/s and 0.26 mL/s, respectively. This implies that the flow rate through the 5 μm filters was more variable than in the 1 μm filters.

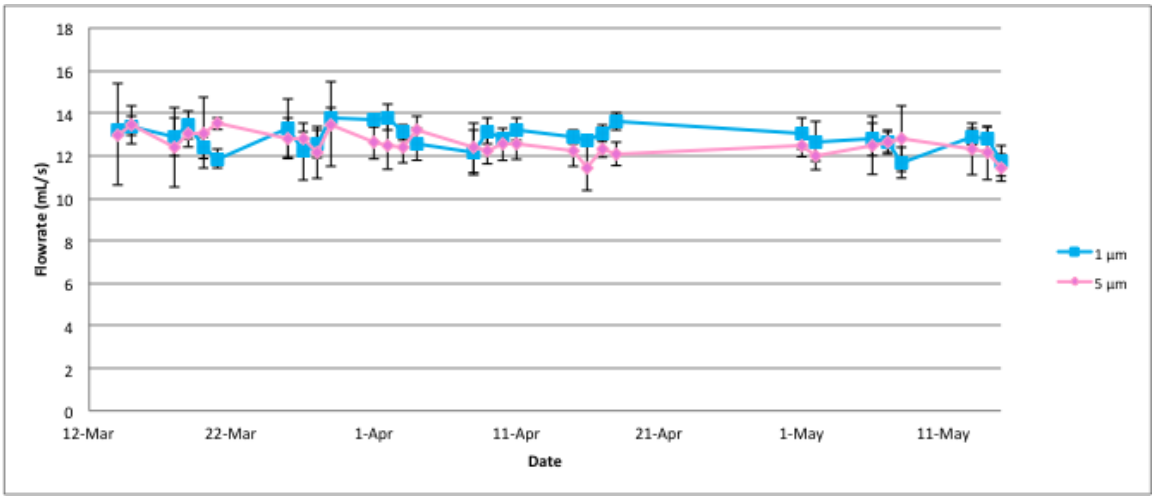

Figure 27: Average string filter flow rate with standard deviations.

Toward the end of the experiment, although the initial flow rate, when the bucket was full of water, was not affected, the flow rate began to slow as the water was reduced to about half of the original volume. This implied that the main sediment buildup occurred on the lower portion of the string filters, as can be seen in both filter types in Figure 28.

Figure 28: 1 µm and 5 µm filters after the experiment commenced.

During the final week of experimentation, the flow rates for the half-full buckets were measured. The results of these tests are shown in Figure 29. The half-full flow rates were affected for both filter types after 8 weeks of experimentation as the time for the

water to run through the systems slowed, but the 5 µm filter was effected slightly more than the 1 µm filter.

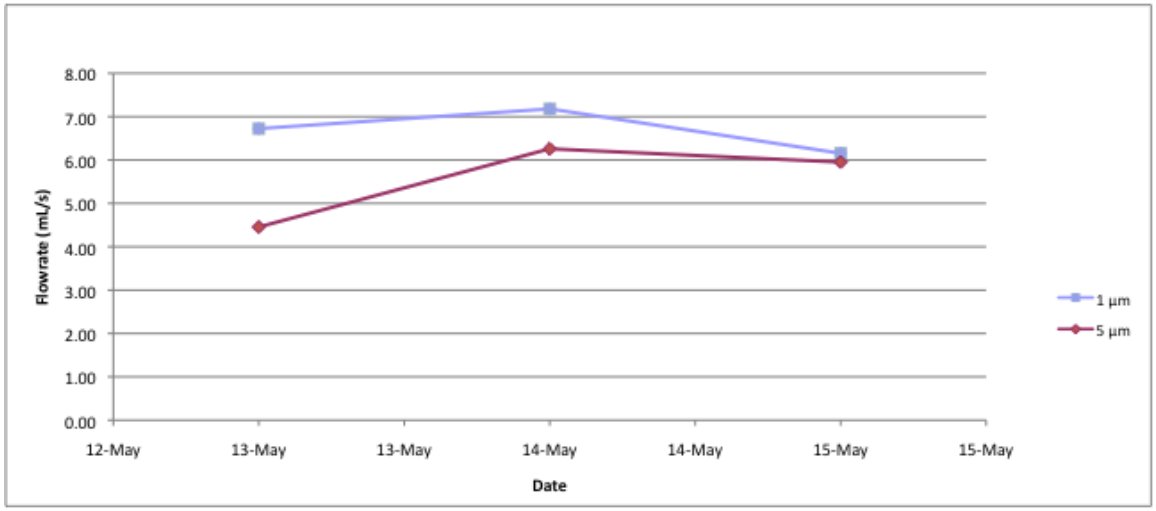

Figure 29: String filter flow rates at half-full volume.

4.1.3 *E. Coli*

Tables 12 and 13, shown in Appendix C, provide summaries of viable *E. coli* measurements collected during the experiment. For most test dates, raw water samples had measureable concentrations of viable *E. coli*, ranging from 2.5 to 230 *E. coli* colonies/100 mL. No *E. coli* colonies were detected in the intermediate samples until the end of week 7. Between 0.6 and 1.3 *E. coli* colonies/100 mL were counted in intermediate samples from the 5 µm filters on three different occasions after that point. The concentrations of *E. coli* in the raw water on these days were between 103 and 230 *E. coli* colonies/100 mL; however, the second chlorination step inactivated the remaining viable *E. coli*. No viable *E. coli* were detected in any of the product water samples. This suggests that the combination of treatment methods used in the GOW system is effective for removal and/or inactivation of *E. coli*. The WHO regulates that there must be zero *E.*

coli colonies in any 100 mL sample of drinking water (WHO, 2008). The MCLs, designated by the US EPA specify that there must be zero detectable *E. coli* colonies in a liter of sample (EPA, 2013). The GOW system successfully meets both of these objectives.

4.1.4 Turbidity

The results of the turbidity measurements, as well as the gage height data in the Wabash River as a function of date, are shown in Figure 30. The detailed turbidity measurements throughout the course of the experiment can be found in tabular form in Appendix D. The turbidity measurements for the 1 μm filters were nearly always slightly higher than for the 5 μm filters. For all samples, turbidity in the final product water was lower than the source (raw) water, as expected. There were many cases, however, that the turbidity in the intermediate water samples was higher than in the raw water. This happened more frequently in the 1 μm filters than in the 5 μm filters. Furthermore, most of these instances took place after the spike in turbidity in the raw water following the rain events. As preciously mentioned, after heavy rain events, river velocities tend to increase due to heavy runoff, which leads to stream bank erosion and higher turbidity in the water (EPA, 2012). The turbidity values were much higher in both filter types following the rain events starting on April 15th, as shown in Figure 30. This spike in turbidity appeared to cause a buildup of sediment on the filters, which may have escaped through with the effluent water in the following runs, explaining the added turbidity in the intermediate water samples. The GAC cartridge was consistently able to bring that turbidity down to comparable levels to the pre-rain events in the final water samples, however.

During the time span of this experiment, the turbidity in the raw Wabash River water ranged from 5.6 to 493 NTU. These minimum and maximum turbidity measurements occurred on April 9th and April 16th, respectively, whereas the minimum and maximum gage height measurements occurred on April 9th and April 15th. The time course trends in raw water turbidity and gage height followed a log-linear relationship, as shown in Figure 32. The effluent turbidity values on the day with minimum raw water turbidity averaged 1.8 NTU for the 1 μm filters and 1.3 NTU for the 5 μm filters. The effluent turbidity values on the day with maximum raw water turbidity averaged 44.7 NTU for the 1 μm filters and 27.6 NTU for the 5 μm filters. The effluent turbidity values never fell below 1 NTU, as specified by the Surface Water Treatment Rule of the US EPA for systems based on direct filtration. The effluent turbidity values for both filter types fell below 5 NTU, or the maximum turbidity limit for systems involving something other than direct filtration, when the influent water was less than or equal to 12 NTU.

The time-course trends in turbidity measurements for the intermediate and product water were similar to those of the raw water. Collectively, these results imply that the filters remove a large fraction of colloidal particles, but some colloids are not removed by the filters. These systems produce effluent water with acceptable turbidity when the source water contains a lower turbidity.

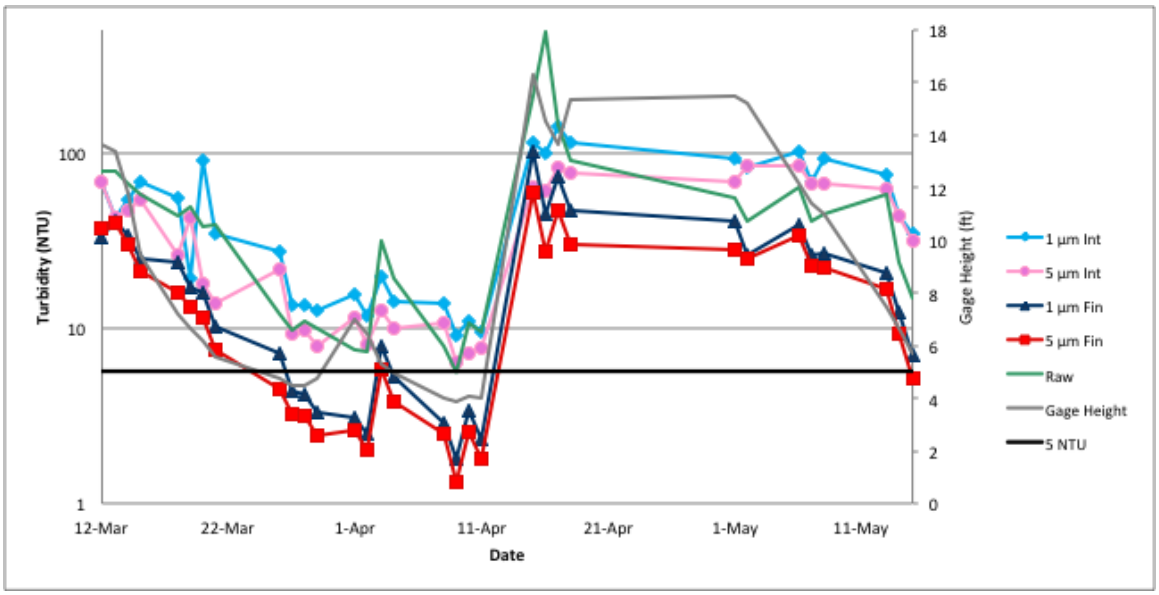

Figure 30: Turbidity and gage height as a function of sample date.

4.1.5 DPD/KI Colorimetric Method

The data in Figure 31 illustrate the free chlorine concentration measurements as a function of time across the test systems. The detailed free chlorine residual measurements throughout the course of the experiment can be found in tabular form in Appendix E. For most test dates, the free chlorine concentration was higher in the intermediate water samples than in the final water samples. This implies that the activated carbon cartridge is effective in removing most of the free chlorine that is applied in the first bucket. Furthermore, the free chlorine concentrations from both buckets were substantially less than the chlorine doses that were applied in each case (3.35 mg/L as Cl_2 and 0.85 mg/L as Cl_2 for buckets 1 and 2, respectively). This suggests that the source water (from the Wabash River) includes compounds that express substantial chlorine demand.

It is also interesting to note that the intermediate and final water samples from the 1 µm filters tended to have higher free chlorine concentration than from the 5 µm filters. This implies that the 1 µm filters may have removed more of the chlorine-demanding substances than the 5 µm filters. This is consistent with a situation in which colloidal particles with sizes ranging from 1 to 5 µm are present in the water. Removal of these colloidal particles could diminish chlorine demand. Also displayed on Figure 31 is the gage height, which had the same trends as the free chlorine residual concentrations throughout the testing period.

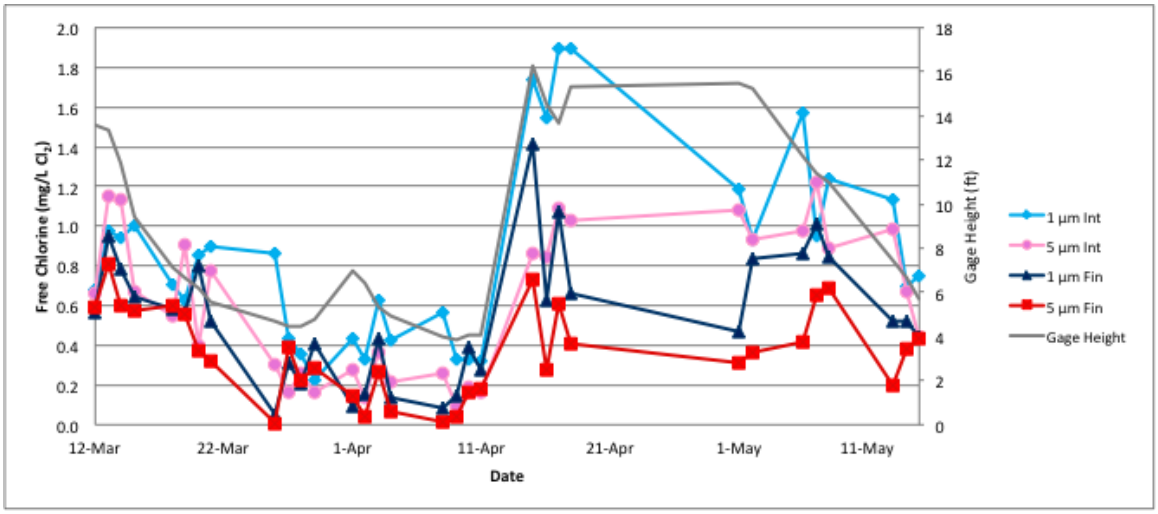

Figure 31: Free chlorine residual and gage height as a function of sample date.

Figure 32 illustrates the total residual chlorine concentration measurements and the gage height data as a function of sample date. The detailed total residual chlorine measurements throughout the course of the experiment can be found in tabular form in Appendix F. In qualitative terms, the trends in the total residual chlorine signals were similar to those described for free chlorine. The total chlorine residual measurements had similar trends to the gage height measurements, just as in the free chlorine samples. The

total chlorine concentration decreased from intermediate to final water samples in mostly all cases. This implies that the activated carbon cartridge was also effective in removing most of the combined chlorine that is applied in the first bucket, just as for free chlorine.

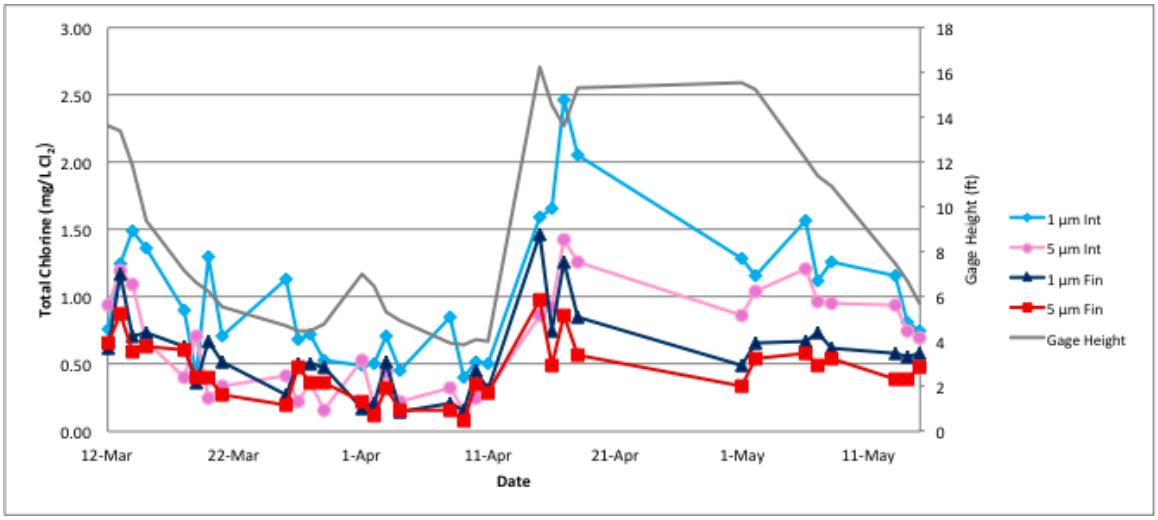

Figure 32: Total chlorine residual and gage height as a function of sample date.

Combined chlorine concentration can be estimated by subtracting the free chlorine signal from the total chlorine signal. A summary of the results of these calculations is provided in Figure 33. The detailed combined chlorine residual measurements throughout the course of the experiment can be found in tabular form in Appendix G. In most cases for the 1 µm filters, the combined chlorine concentration decreased from intermediate to final sample. This trend was less evident for the 5 µm filters, however, where the opposite was true during roughly half of the testing days. This implies that the 5 µm filters may not have been able to remove some of the particles that react with the secondary chlorine dose to form combined chlorine that the 1 µm filters were able to remove. Furthermore, most of the combined chlorine concentrations were substantially less than the free chlorine concentrations during every day of testing. The combined chlorine

concentrations were negligible on some days of testing for both the intermediate and final samples.

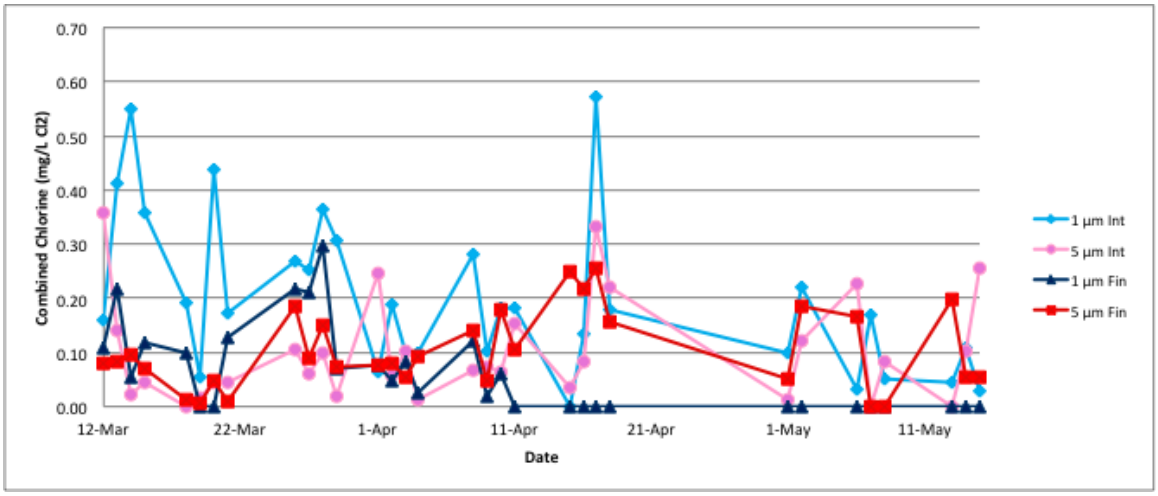

Figure 33: Combined chlorine residual as a function of sample date.

4.1.6 MIMS

The MIMS protocol used for these measurements was designed to measure the concentrations of 11 volatile DBPs in water: $CHCl_3$, $CHCl_2Br$, $CHClBr_2$, $CHBr_3$, CNCl, CNBr, CH_3NCl_2, $CHCNCl_2$, NH_2Cl, $NHCl_2$, and NCl_3 (Weng et al., 2012); (Weaver et al., 2009). Of these compounds, only $CHCl_3$ was observed to be present above the detection limit in the chlorinated water samples.

Figure 34 provides a summary of the measured chloroform concentrations for intermediate and final water samples. The detailed MIMS measurements throughout the course of the experiment can be found in tabular form in Appendix H. The chloroform concentrations were generally higher in the final water samples than in the intermediate water samples. The chloroform concentrations in the intermediate water samples for the 1

μm filters were consistently slightly higher than those of the 5μm filters. The concentrations in the final water samples for both filter types were nearly identical. To prove the validity of this statement, an independent-samples t-test was performed on the final chloroform concentrations for the two filter types. The results of this t-test are shown in Table 24 in Appendix H. There was a 95% confidence level that the chloroform concentrations in the effluent water for both filter types were indistinguishable during every day of experimentation, except on March 15th. Although the nominal pore size opening of the string filter might have some effect on the chloroform concentration, the rest of the GOW filtration system appears to eliminate the discrepancy, resulting in consistently low chloroform concentrations.

As mentioned, the US EPA has established a MCL of 80 μg/L for total trihalomethanes (TTHMs) in drinking water samples, as shown by the red line on the figure. Chloroform is an important measurement because it is often used as an indicator for the presence of other DBPs. According to a survey of DBPs in US drinking water done by the US EPA, high levels of chloroform, above 60 μg/L, correspond to the likelihood of high concentrations of other THMs and other DBPs. A concentration of chloroform under 20 μg/L, however, does not lead to any conclusions about the other DBP concentrations in water (Weinberg, Krasner, Richardson, & Thruston, 2002). Chloroform was the dominant THM in chlorinated water samples. The other three THM compounds that comprise the TTHM signal in drinking water samples were present at concentrations that were below their respective limits of detection in these experiments. Therefore, TTHM production in the GOW system is in compliance with relevant drinking water regulations.

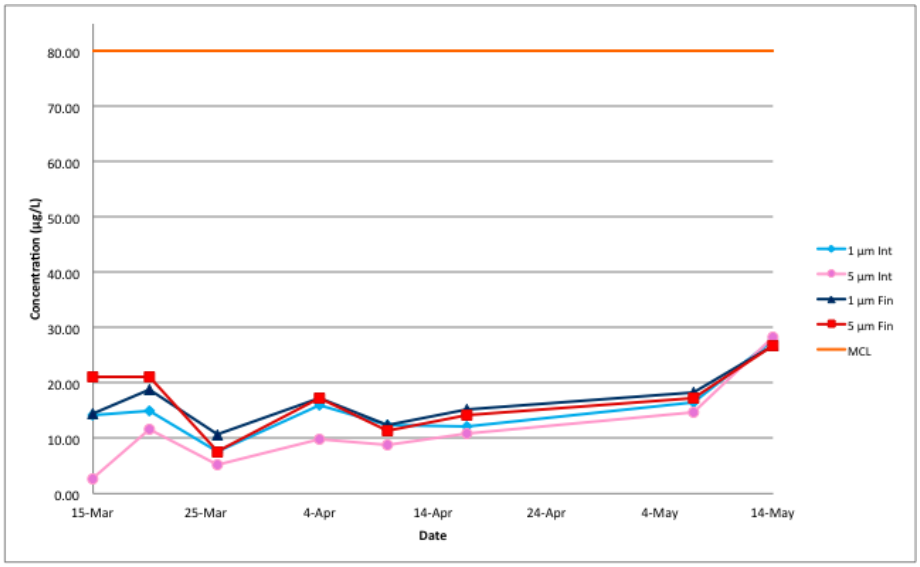

Figure 34: Chloroform concentrations in intermediate and final water samples.

Table 3 displays the inorganic combined chlorine concentrations, or the sum of the monochloramine, dichloramine and trichloramine concentrations measured in the water samples via MIMS. These concentrations are mostly all below the combined chlorine concentrations measured with the DPD/KI colorimetric method. This implies that the water samples must have contained organic chloramines, which may have interfered with the combined chlorine residual concentration measurements

Table 3: Inorganic Combined Chlorine Concentrations (mg/L).

	15-Mar	20-Mar	26-Mar	4-Apr	10-Apr	17-Apr	7-May	14-May
1 µm Int	3.4E-02	1.8E-02	6.7E-02	3.0E-02	3.0E-02	1.6E-01	3.3E-02	1.4E-02
5 µm Int	5.0E-03	5.8E-03	2.4E-02	2.3E-03	1.1E-02	7.6E-02	2.2E-02	4.9E-03
1 µm Fin	1.0E-02	1.5E-02	1.6E-02	6.6E-03	4.4E-03	7.2E-02	1.7E-02	7.2E-03
5 µm Fin	1.5E-02	1.3E-02	9.5E-03	5.3E-03	5.6E-03	6.7E-02	1.5E-02	7.8E-03

4.1.7 UV Absorbance 254

Figure 35 provides a summary of the measured absorbance values for a wavelength of 254 nm for the intermediate and final water samples, as well as for the raw water. The detailed UV_{254} Absorbance measurements throughout the course of the experiment can be found in tabular form in Appendix I. The minimum and maximum absorbance values were consistent with the gage height measurements, which are also displayed in Figure 35. The mimimum and maximum for both measurements occurred on April 9th and April 15th, respectively. In other words, when the gage height is high and the water contains a higher turbidity, the water contains a higher amount of suspended solids, and presumably more DBP precursor material. The detailed scan graphs from 400-200 nm for those two days are shown in Figures 46 and 47 in Appendix I. The time-course trends in absorbance measurements were similar to those of the raw water and the turbidity measurements.

Absorbance generally decreased from intermediate to final water samples. This was consistent with a situation in which UV-absorbing compounds are removed by filtration or adsorption, or by reactions in which chlorine attacks unsaturated bonds. This is also consistent with the process of "bleaching", which is a well-known effect of chlorine addition.

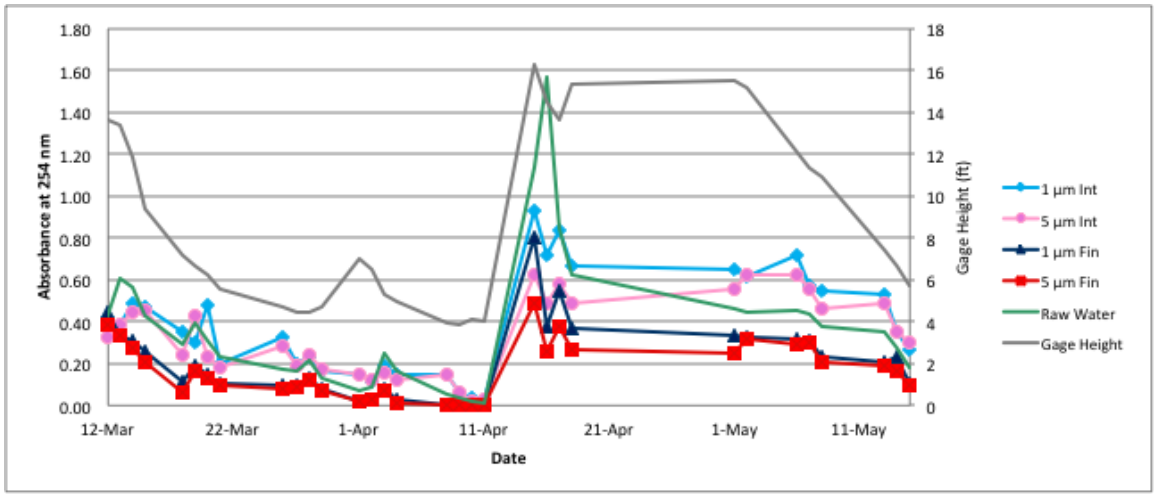

Figure 35: UV Absorbance and Gage Height measurements as a function of sample date.

4.2 Clogging Rate

The results of the clogging rate tests are shown in Figures 36-38. Each data point in Figure 36 corresponds to the mean flow rate measurement taken at that time The average clogging rate for each filter type was found by fitting a trendline to the data sets. The clogging rates for both the 1 µm and the 5 µm filters were nearly identical, at an average rate of -0.55 mL/s/hr, as shown from the trendline equations in Figure 36. Figure 37 shows the flow rate vs. time in the 1 µm filters, and Figure 38 shows the flow rate vs. time in the 5 µm filters. Some variability occurred in the flow rates through each filter type. The detailed flow rate measurements throughout the course of this experiment can be found in Table 27 in Appendix J.

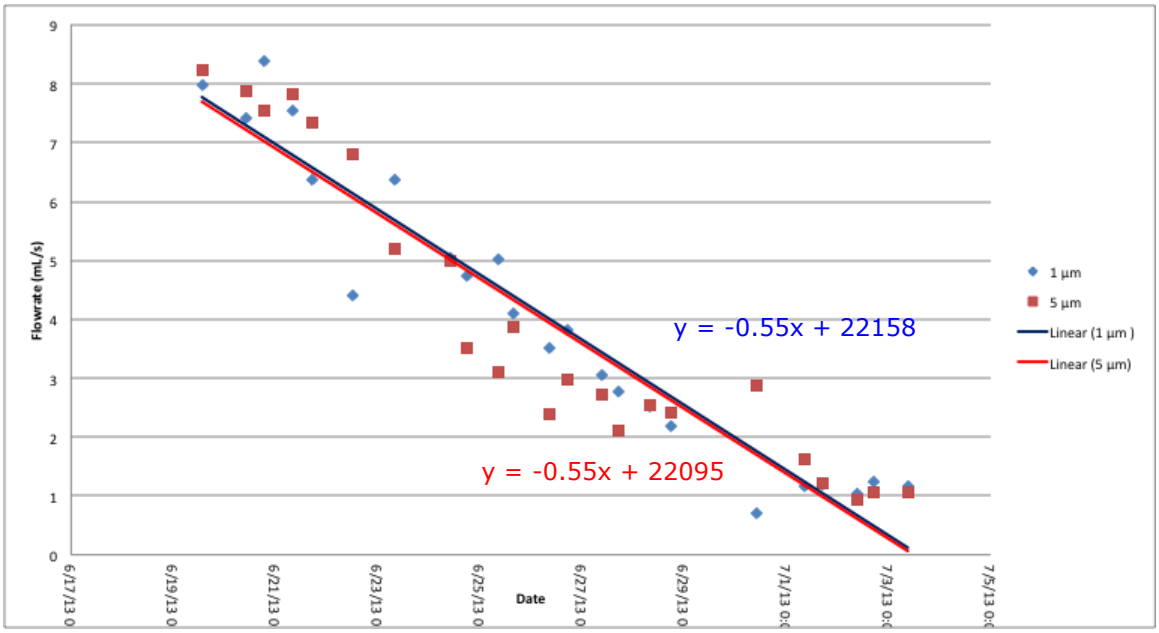

Figure 36: Clogging rates in the 1 µm and 5 µm filters.

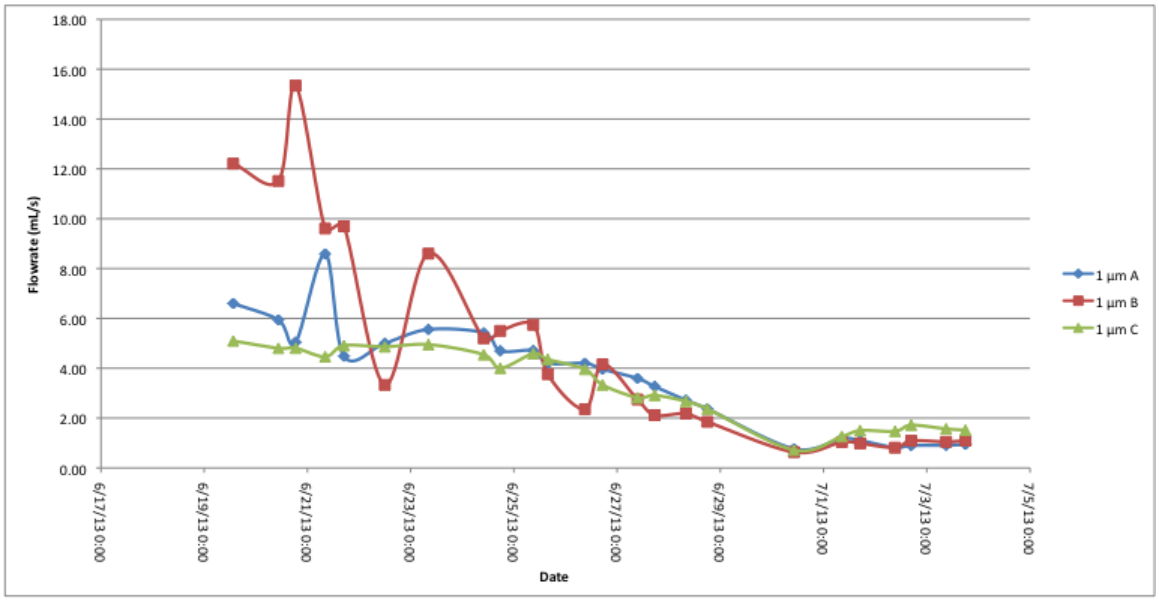

Figure 37: Flow rate as a function of time in the 1 µm filters.

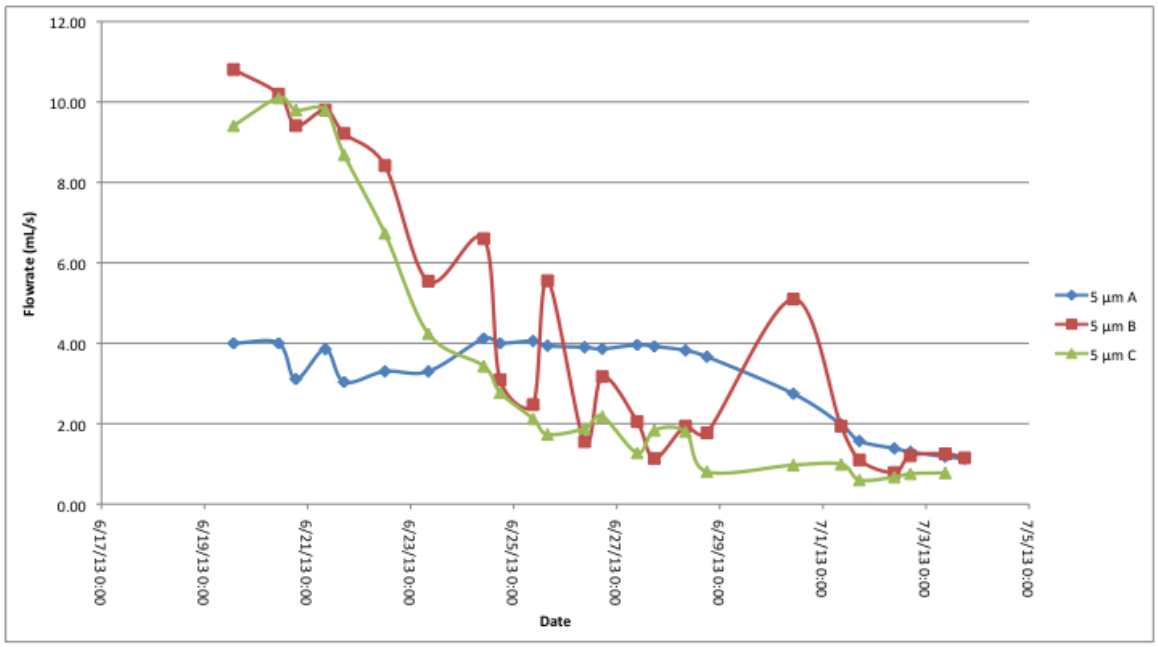

Figure 38: Flow rate as a function of time in the 5 µm filters.

The total volume of water that flowed through the filters throughout the course of the experiment was calculated as the average flow rate in consecutive runs multiplied by the elapsed time between those flow rate measurements. The point of clogging in the filters was defined as when the filters reached a flow rate of 2 mL/s, corresponding to a filtration time of to 2.8 hours. The string filters should be replaced once the flow rate slows to this point. The total average volume of water that flowed through the three 1 µm filters was 4037 Liters. This corresponds to a total of 202 20-Liter filter runs. Assuming the users run their filters once a day, 365 days a year, the 1 µm filters would ultimately last 0.55 years, or 6.6 months, until the string filters needed to be replaced. Alternatively, the total average volume of water that flowed through the three 5 µm filters was 3828 Liters, corresponding to a total of 191 20-Liter filter runs. With the same assumptions, the 5 µm filters would ultimately last 0.52 years, or 6.3 months, until the

string filters needed replaced. The results of these calculations are shown in Table 4. One of the filters after clogging occurred is displayed in Figure 39. These detailed calculations can be found in Table 28 in Appendix J.

Table 4: Clogging rate projections.

Filter	**V_T (L)**	**Number of runs system can sustain before clogging (V_T/V_{bucket})**	**Years to clogging**
1 µm A	3903	195	0.53
1 µm B	4814	241	0.66
1 µm C	3395	170	0.47
5 µm A	3476	174	0.48
5 µm B	4115	206	0.56
5 µm C	3894	195	0.53
1 µm average	*4037*	*202*	*0.55*
1 µm average	*3828*	*191*	*0.52*

Figure 39: String filter after clogging.

To better understand the suspended solids in the water that led to the clogging of the filters for this experiment, the turbidity of the source water was measured during each day of testing. The TSS measurements in the effluent contact chamber were obtained from the West Lafayette WWTP staff, as well. The results of these measurements are shown in Figure 40. The detailed measurements throughout the course of this experiment can be found in Table 29 in Appendix J. The algae in the clarifiers was flushed through the effluent contact chamber in the WWTP periodically throughout the course of the experiment, causing the turbidity spikes in the water.

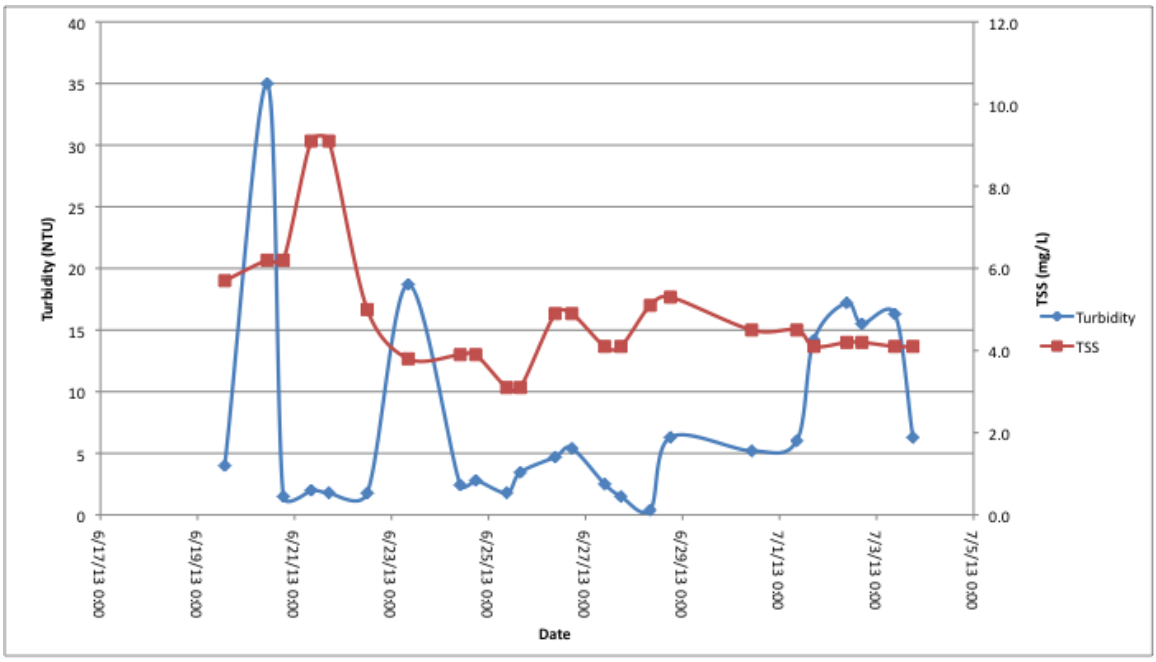

Figure 40: Turbidity and TSS measurements as a function of sample date.

4.3 Inactivation Assays

The results of the phage experiments are shown in Tables 5-8. The detailed results for each plaque assay can be found in Appendix K. Table 5 shows the results of the plaque assays done on the ΦS1 phage suspension with Milli-Q water, both with and without the

first free chlorine dose of 67 mg Cl_2. As one can infer from this table, the free chlorine dose achieved over seven logs of inactivation for the ΦS1 phage suspension in Milli-Q water. The sodium thiosulfate did not alter the ΦS1 phage titer significantly.

Table 5: Results of plaque assays for Milli-Q water and free chlorine dose 1 with ΦS1 phage suspension.

Solution Components	**Titer (pfu/mL)**
φS1	1.83E+08
φS1 and Sodium Thiosulfate	1.87E+08
φS1 and Free Chlorine Dose 1 and Sodium Thiosulfate	<10

Table 6 shows the results of the plaque assays done on the T4 phage suspension with Milli-Q water, both with and without the first free chlorine dose of 67 mg Cl_2. As one can infer from this table, the free chlorine dose achieved over four logs of inactivation for the T4 phage suspension with sodium thiosulfate. The sodium thiosulfate did not alter the T4 phage titer significantly.

Table 6: Results of plaque assays for Milli-Q water and free chlorine dose 1 with T4 phage suspension.

Solution Components	**Titer (pfu/mL)**
T4	3.60E+06
T4 and Sodium Thiosulfate	2.22E+05
T4, Free Chlorine Dose 1 and Sodium Thiosulfate	6.33E+00

Table 7 shows the results of the plaque assays done on the φS1 phage suspension with Wabash River water without treatment, after the first chlorine dose of 67 mg Cl_2, and after the filtration process with the second chlorine dose of 17 mg Cl_2. As one can infer from this table, the first free chlorine dose inactivated about 1.5 logs of the ΦS1 phage suspension, and the second free chlorine dose inactivated about 1.5 logs of the ΦS1 phage suspension. This implies a total log reduction of three logs in the total GOW treatment system. Furthermore, the sodium thiosulfate did not alter the ΦS1 phage titer significantly.

Table 7: Results of plaque assays for Wabash River water and free chlorine doses 1 and 2 with φS1 phage suspension.

Solution Components	**Titer (pfu/mL)**
φS1	1.42E+07
φS1 and Sodium Thiosulfate	2.50E+07
φS1, Free Chlorine Dose 1 and Sodium Thiosulfate	7.23E+05
φS1 Free Chlorine Dose 2 and Sodium Thiosulfate	1.63E+04

Table 8 shows the results of the plaque assays done on the T4 phage suspension phage suspension with Wabash River water without treatment, after the first chlorine dose of 67 mg Cl_2, and after the filtration process with the second chlorine dose of 17 mg Cl_2. As one can infer from this table, the first free chlorine did not seem to affect the T4 phage suspension, and the second free chlorine dose yielded a total inactivation in the T4 phage suspension of less than one log. This implies that the T4 bacteriophage is more resistant to disinfection than the φS1. The sodium thiosulfate did not alter the T4 phage titer

significantly, just as in the other tests. This implies that sodium thiosulfate can be used to dechlorinate the water for tests such as these.

Table 8: Results of plaque assays for Wabash River water and free chlorine doses 1 and 2 with T4 phage suspension.

Solution Components	**Titer (pfu/mL)**
T4	3.20E+06
T4 and Sodium Thiosulfate	3.19E+06
T4, Free Chlorine Dose 1 and Sodium Thiosulfate	3.26E+06
T4 Free Chlorine Dose 2 and Sodium Thiosulfate	1.27E+06

There were likely many other contaminants in the natural water supply that interfered with the chlorine disinfection for the phage suspensions. When measuring the free chlorine concentration in the Milli-Q water through the first chlorine dose period, the free chlorine concentration dropped to 0.67 mg/L as Cl_2 after the first chlorine dose. When measuring the free chlorine concentration in the Wabash River water through the chlorine dose period, the free chlorine concentration dropped to 2.5 mg/L as Cl_2 after the first chlorine dose and 0.3 mg/L as Cl_2 after the second chlorine dose. Using this data and the Chick-Watson kinetics as defined in section 2.5.5, the average disinfection rate constants for φS1 and T4 in both water sources were calculated. The average disinfection rate constant for φS1 in the first chlorine dose in the GOW system with Milli-Q water was 0.51 L/mg-min, and the average disinfection rate constant for T4 in the first chlorine dose in the GOW system with Milli-Q water was 0.17 L/mg-min. The average disinfection rate constant for φS1in the GOW system with Wabash River water was 0.08 L/mg-min,

and the average disinfection rate constant for T4 in the GOW system with Wabash River water was 0.04 L/mg-min. As expected, the rate constants were higher with the Milli-Q water since both phage suspensions experienced more inactivation in that, pure water source. Also, φS1 has a higher rate constant, meaning that it is more sensitive to inactivation. The details of these calculations can be found in Table 44 in Appendix K.

4.4 Source Water Testing in Haiti

Samples were collected from six different water sources during the trip to Haiti. The results of *E. coli* MPN measurements by the Compartment Bag Test, as well as the confidence intervals and the turbidity measurements for those water samples are shown in Table 9.

Table 9: Water quality data from source water in Belladere, Croix Fer, and Dos Celle.

	Source	**Location**	**MPN/100mL**	**Upper 95% Confidence Limit Value/100 mL**	**Turbidity (NTU)**
1	Spring	Ma Pou (outside Dos Celle Community)	13.6	83.06	0.19
2	Rainwater Catchment Basin	Road between Belladere and Croix Fer	1.5	7.81	0.40
3	Spring	Outside church in Croix Fer	48.3	451.91	1.15
4	Spring	Outside Dam in Croix Fer	1.5	7.81	1.3
5	Spring	Near River in Croix Fer	13.6	83.06	0.57
6	River	Croix Fer	1.5	7.81	6.64

The first source was a spring in Ma Pou, a small area about 30 minutes from the heart of Dos Celle on foot. This water source was low in turbidity, but fairly high in *E. coli* concentration, proving the need for disinfection. The WHO specifies that water under 5 NTU is acceptable for consumption, but the water should, ideally, be under 0.1 NTU. Furthermore, as previously mentioned, the WHO regulates that there must be zero *E. coli* colonies in any 100 mL sample of drinking water (WHO, 2006). Figure 41 shows a woman from the Dos Celle community collecting water for her family from that water source.

Figure 41: Woman collecting water from spring in Ma Pou outside Dos Celle Community (source 1).

The second water source was a rainwater catchment basin on the road between Belladere and Croix Fer. This source was a relatively shallow water pond, with rocks lining the bottom. During collection of this water sample, a woman and her daughter were there, collecting water for their family. The woman was scooping the clear water off the top of the pond with a shallow tin bowl in order to avoid sediment in the water, as shown in

Figure 42. This water source contained a relatively low turbidity, and fairly low *E. coli* concentration.

Figure 42: Rainwater catchment basin between Belladere and Croix Fer (source 2).

Several water samples were collected at Croix Fer. Specifically, samples were obtained from three different springs, as well as the river. As shown in Table 8, the spring by the church had the highest *E. coli* concentration out of all the water samples, followed by the spring by the river. That spring (source 5), as shown in Figure 43, was downstream of an irrigation ditch, so it is highly likely that the spring water was contaminated from the animal excrement applied to the crops as fertilizer.

Figure 43: Spring near the river in Croix Fer (source 5).

The river and the spring by the dam in Croix Fer had the lowest *E. coli* concentrations, but the turbidity in the river water was relatively high, as compared to the other sources, making that water source a less attractive option. The river water source is shown in Figure 44.

Figure 44: River in Croix Fer (source 6).

Figures 45-46 show the comparison of the turbidity measurements obtained from the source water in Haiti and the water used for experimentation. The data points for the water from the West Lafayette WWTP and the Wabash River water represent the mean raw water turbidity measurements taken throughout the course of experimentation. The error bars for those data points represent the standard deviations in those measurements. As one can infer from the two figures, the water from both the WWTP and the Wabash River contained a higher mean turbidity than all of the samples collected while in Haiti, and the variability shown by the standard deviations amplified this difference. Furthermore, the Wabash River water turbidity measurements were much higher than the water from the WWTP. This implies that the water used for experimentation was much worse, in terms of turbidity, than the source water tested in Haiti during the time periods studied. The GOW system performance observed throughout these experiments was, therefore, likely worse than what the users in Haiti would experience.

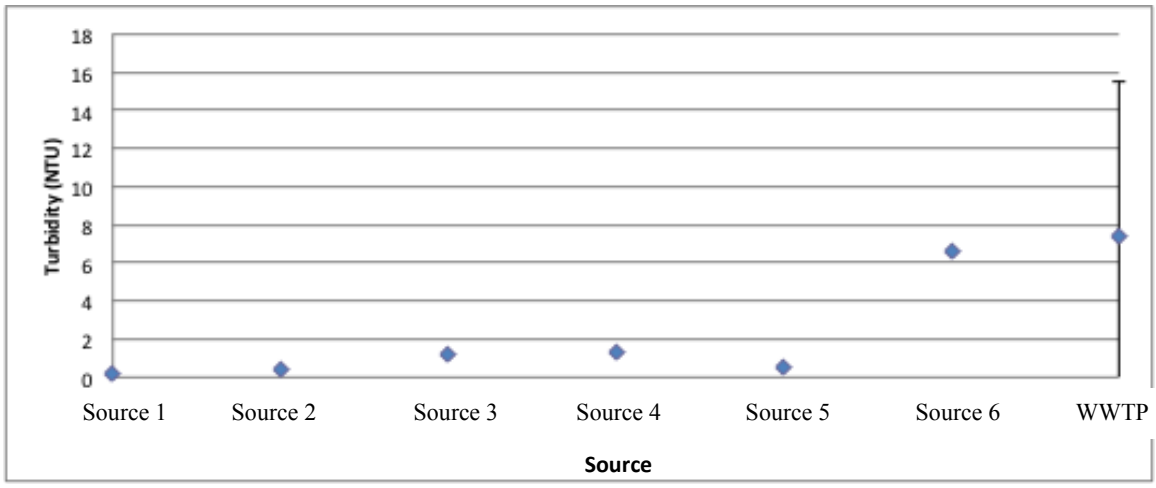

Figure 45: Turbidity in the source water from Haiti and the WWTP water used for experimentation.

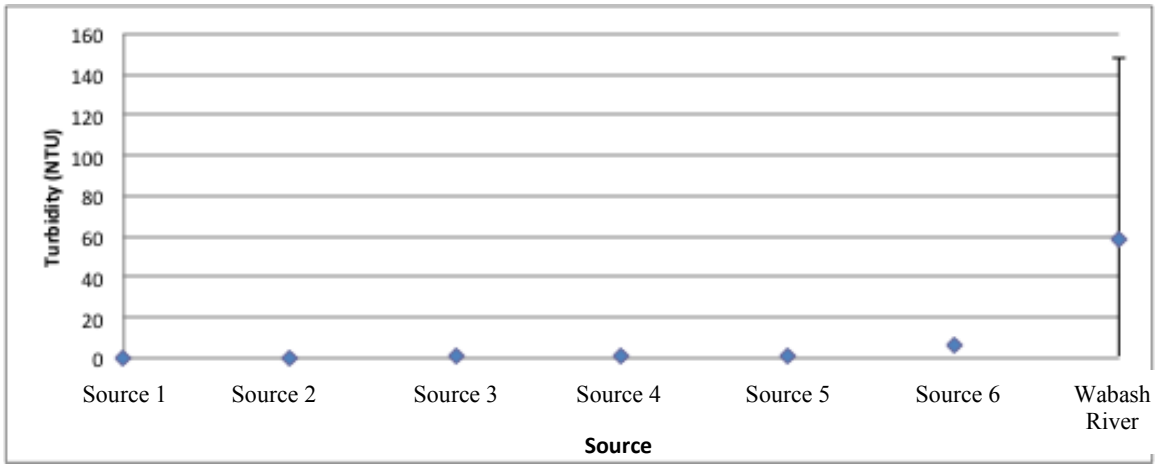

Figure 46: Turbidity in the source water from Haiti and the Wabash River water used for experimentation.

During in the visit to Haiti with the GOW team, 112 GOW filtration units were distributed: 42 units in Dos Celle, 36 units in Croix Fer, and 34 units in Belladere. Most of the community members actively participated in the training sessions, and were enthusiastic during the distribution sessions. Figure 47 shows two women walking home from the distribution session in Dos Celle with their new GOW filters.

Figure 47: Two women leaving Dos Celle with their new GOW filters.

CHAPTER 5. CONCLUSIONS

Little difference was noted in the flow rates between the 1 μm and the 5 μm string filters throughout the course of the experiment. Both filter types successfully inactivated the *E. coli* in the source water.

Both filters were able to remove a large fraction of the colloidal particles, but some colloids were not removed during the filtration process. The effluent turbidity values throughout the experiment ranged from 1.79 NTU to 101.33 NTU for the 1 μm filters, and from 1.33 NTU to 59.63 NTU for the 5 μm filters. The final turbidity measurements for the 1 μm filters were usually slightly higher than for the 5 μm filters, implying that the 1 μm filter does not remove more suspended solids than the 5 μm filters. The effluent turbidity values for both filter types fell below 5 NTU when the influent water was less than or equal to 12 NTU.

The total chlorine concentrations followed the same trends as the free chlorine concentrations in both filter types. Free and total chlorine concentrations decreased in the final water samples for both filter types. The granular activated carbon was effective in removing most of the free and total chlorine from the first chlorine dose. The intermediate and final water samples from the 1 μm filters tended to have higher free and total chlorine concentrations than from the 5 μm filters. The combined chlorine

concentrations were substantially less then the free chlorine concentrations during every day of testing. The inorganic combined chlorine concentrations in the water samples measured by MIMS were mostly all well below the combined chlorine residuals measured with the DPD/KI colorimetric method, implying that organic chloramines must have been formed during the disinfection process. During the MIMS testing, chloroform ($CHCl_3$) was the only DBP observed to be present above the detection limit in the chlorinated water samples. The maximum average concentration measured in the effluent water samples from both the 1 μm and the 5 μm filters was 27 μg/L. These concentration measurements are well below the MCL of 80 μg/L for TTHMs, as established by the US EPA. The chloroform concentrations in the effluent water from both filter types were nearly identical throughout the course of the experiment.

The UV absorbance measurements at 254 nm followed a similar pattern to the turbidity measurements, implying that more DBP precursor material is present when the turbidity is at a high value. The absorbance generally decreased from intermediate to final water samples, meaning the UV-absorbing compounds were sucessfully removed by the filtration or adsorption in the GAC, or by the reactions in the secondary chlorine dose. The absorbance values and the time course trends between the two filter types were very similar.

The clogging rates for the 1 μm string filters and the 5 μm string filters were nearly identical, at an average rate of -0.55 mL/s/hr. The 1 μm filter allowed an average of 4037 liters of water through the filter, and the 5 μm filter allowed an average of 3828 liters of water through the filter before clogging occurred. This corresponds to approximately 202

runs for the 1 μm filters and 191 runs for the 5 μm filters before clogging occurs.

The GOW system achieved over seven logs of inactivation for the ΦS1 phage suspension and over four logs of inactivation for the T4 phage suspension when used with Milli-Q water. When used with the Wabash River water, however, the GOW system achieved approximately three logs of inactivation for the ΦS1 phage suspension and less than one log of inactivation for the T4 phage suspension. The natural water source contained many contaminants that interfered with the chlorine disinfection for the phage suspensions. Using the Chick-Watson kinetics and Ct data from experimentation with the Milli-Q water, the disinfection rate constant for ΦS1 in the first chlorine dose of the GOW system was 0.51 L/mg-min, and the disinfection rate constant for T4 was 0.17 L/mg-min. In the Wabash River water, the average disinfection rate constant for ΦS1 in the GOW system was 0.08 L/mg-min, and the average disinfection rate constant for T4 was 0.04 L/mg-min. More viral inactivation occurred in the Milli-Q water, and ΦS1 is more sensitive to inactivation than T4.

The *E. coli* concentrations in the six water sources collected while in Haiti ranged from 1.5 MPN of *E. coli* per 100 mL of the sample to 48.3 MPN of *E. coli* per 100 mL of sample. The experiments proved that the GOW systems can effectively inactivate these levels of *E. coli* concentrations. The turbidity measurements ranged from 0.19 NTU to 6.64 NTU. This water was dramatically less turbid than the Wabash River water used for testing. The source water samples were also generally less turbid than the water used for the clogging rate experiments at the effluent contact chamber at the West Lafayette WWTP. Under the time periods studied, the water used in experiments at Purdue

University in Spring 2013 were worse than what the GOW filter users would experience in Haiti.

Further studies could be done to ensure that the nominal pore size openings in the string filters are correct, which was not evident in this study. Further studies could also be done to compare the clogging rates in the filters at a range of turbidity values in order to better understand the lifespan of the filters under variable conditions.

BIBLIOGRAPHY

BIBLIOGRAPHY

Alekal, P. Y. (2005). *Appropriate Water Treatment for the Nyanza Province of Kenya*. MIT.

Allgeier, S., Allspach, B., & Vickers, J. (2003). *Membrane Filtration Guidance Manual*. EPA.

American Water Works Association. (2006). *Water chlorination/chloramination practices and principles*.

Aquagenx. (2013). Compartment Bag Test: Instructions for Use. Winston-Salem, North Carolina, Unites States of America.

BBC. (2013, May 8). *Haiti cholera victims threaten to sue the UN*. Retrieved June 28, 2013, from News: Latin America & Caribbean: http://www.bbc.co.uk/news/world-latin-america-22458006

BBC. (2012, October 17). *Haiti Country Profile*. Retrieved May 2013, from BBC News: http://news.bbc.co.uk/2/hi/americas/country_profiles/1202772.stm

Blatchley, E. R., & Donnermaier, M. M. (2003). Disinfection efficacy or organic chloramines. *Water Research* (37), 1557-1570.

Borucke, M. J. (2002). *Filtration of Giardia cysts from Haitian Drinking Water*. Thesis, MIT, Civil and Environmental Engineering.

Brown, J., Outlaw, T., Clasen, T., Wu, J., & Sobsey, M. *Safe Water For All: Harnessing the Private Sector to Reach the Underserved*. World Bank Group, International Finance Corporation.

Carroll, R. (2008, November 7). *Global Development*. Retrieved May 2013, from The Guardian: http://www.guardian.co.uk/world/2008/nov/08/haiti-hurricanes

CDC. (2012, July 11). *Centers for Disease Control and Prevention*. Retrieved June 18, 2013, from Parasites - Giardia: http://www.cdc.gov/parasites/giardia/gen_info/faqs.html

CDC. (n.d.). *Disinfection By-Products and the Safe Water System*. Retrieved July 5, 2013, from http://www.cdc.gov/safewater/publications_pages/thm.pdf

CDC. (2012, March 2012). *Household Water Treatment*. Retrieved June 6, 2013, from Centers for Disease Control and Prevention: http://www.cdc.gov/safewater/household-water.html

CDC. (n.d.). *Safe Water Systems for a Developing World*. Retrieved June 6, 2013, from http://www.cdc.gov/safewater/manual/sws_manual.pdf

CDC. (2012, October 10). *Solar Disinfection*. Retrieved June 6, 2013, from Household Water Treatment: http://www.cdc.gov/safewater/PDF/Solar2011final.pdf

CIA. (2013, May 7). *Central America and Caribbean: Haiti*. Retrieved May, 2013

Clasen, T., & Edmondson, P. (2006). Sodium dichloroisocyanurate (NaDCC) tablets as an alternative to sodium hypochlorite for the routine treatment of drinking water at the household level. *International Journal of Hygiene and Environmental Health , 209*, 173-181.

Crittenden, J. R., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2012). *Water Treatment Principles and Design* (3rd Edition ed.). USA: John Wiley & Sons, Inc.

EPA. (2010). *Comprehensive Surface Water Treatment Rules Quick Reference Guide: Systems Using Conventional or Direct Filtration* . Office of Water.

EPA. (2013, June 3). *Drinking Water Contaminants*. Retrieved July 8, 2013 from United States Environmental Protection Agency: http://water.epa.gov/drink/contaminants/index.cfm#one

EPA. (2000). *Improved Enumeration Methods for the Recreational Water Quality Indicators: Enterococci and Escherichia coli*. Office of Science and Technolog, Washington DC.

EPA. (2013, June 3). *National Primary Drinking Water Regulations*. Retrieved July 5, 2013, from Drinking Water Contaminates: http://water.epa.gov/drink/contaminants/index.cfm#Byproducts

EPA. (2012, March 6). *Turbidity*. Retrieved July 8, 2013 from United States Environmental Protection Agency: http://water.epa.gov/type/rsl/monitoring/vms55.cfm

EPA. (2004). Turbidity Requirements. In *Long Term 1 Enhanced Surface Water Treatment Rule Turbidity Provisions* (pp. 7-9). United States of America.

EPA. (2000, September). *Wastewater Technology: Granular Activated Carbon Absorption and Regeneration*. Retrieved June 24, 2013, from http://water.epa.gov/scitech/wastetech/upload/2003_05_15_mtb_carbon_absorption.pdf

EPA. (2012, March 6). *Water Treatment Process*. Retrieved June 3, 2013, from Environmental Protection Agency: http://water.epa.gov/learn/kids/drinkingwater/watertreatmentplant_index.cfm

Frerichs, R. R. (n.d.). *Index Case at 40 Broad Street*. Retrieved June 3, 2013, from UCLA Department of Epidemiology: http://www.ph.ucla.edu/epi/snow/indexcase.html

Gagdil, A. (2008). Safe and Affordable Drinking Water for Developing Countries. In *Physics of Systainable Energy* (pp. 176-191). Berkely, CA, United States of America: Am. Ist. Phys.

GE. (2013). *Handbook of Industrial Water Treatment*. Retrieved July 3, 2013, from GE Power & Water: http://www.gewater.com/handbook/ext_treatment/ch_6_filteration.jsp

Gift of Water. (2013). *Gift of Water ... is the Gift of Life*. Retrieved May 2013, from www.giftofwater.org

Haggerty, R. (1991). *Haiti - a country study*. Federal Research Division, Library of Congress.

Huisman, L., & Wood, W. E. (1974). *Slow Sand Filtration*. WHO, Geneva.

Jafvert, C. T., & Valentine, R. L. (1992). Reaction Scheme for the Chlorination of Ammoniacal Water. *Environmental Science Technology , 26* (3), 577-585.

Jurenka, B. (2010, September 20). *Granular Activated Carbon*. Retrieved June 24, 2013, from Reclamation: Managing Water in the West: http://www.usbr.gov/pmts/water/publications/reportpdfs/Primer%20Files/07%20-%20Granular%20Activated%20Carbon.pdf

Kramer, E., & Tobin, V. (2003, March 10). *Lack of clean water robs children of health, education*. Retrieved May 2013, from Unicef: http://www.unicef.org/media/media_7596.html

Lantagne, D. S. (2001). *Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filters*. Alethia Environmental, Allston.

Lantagne, D. S. (2001). *Trihalomethane Formation in Rural Household Water Filtration Systems in Haiti*. Thesis, MIT, Civil and Environmental Engineering.

LeChevallier, M. W., & Au, K.-K. (2004). *Water Treatment and Pathogen Control*. World Health Organization. IWA.

Leger, D. L. (2012, January 8). *Cholera cripples Haiti, two years after quake*. Retrieved May 2013, from USA Today: http://usatoday30.usatoday.com/news/world/story/2012-01-05/haiti-cholera-outbreak/52419464/1

Levine, A. (2011, June 18). *Drinking Water and Public Health in 19th Century Philadelphia*. Retrieved June 6, 2013, from The History of Philadelphia's Watersheds and Sewers: http://www.phillyh2o.org/filtration.htm

Linn, L., Eberwine-Villagran, D., & Oliel, S. (2013, March 13). *PAHO/WHO calls for international funding of new Haiti cholera plan*. (PAHO/WHO) Retrieved June 26, 2013, from One Team against Cholera: http://new.paho.org/colera/?p=326

Marini, A., & Gragnolati, M. (2003). *Malnutrition and Poverty in Guatamala*. World Bank, Human Development Sector Unit.

Mayer, G. (2010, February 17). *Bacteriophage*. Retrieved July 5, 2013 from Microbiology and Immunology: http://pathmicro.med.sc.edu/mayer/phage.htm

Mclintock, N. C. (2003). *Agroforestry and sustainable resource conservation in Haiti: A Case Study*. NCSU, Raleigh.

Miller, E. S., Kutter, E., Mosig, G., Arisaka, F., Kunisawa, T., & Ruger, W. (2003). Bacteriophage T4 Genome. (A. S. Microbiology, Ed.) *Microbiology and Molecular Biology Reviews , 67* (1), 86-156.

Ongerth, J. E., & Pecoraro, J. P. (1996). Electrophoretic Mobilityh of Cryptosporidium Oocysts and Giardia Cysts. *J Environ. Eng* , 228-231.

Onuoha, O. (2012). *Combined Global and African Ranking - 25 Country Populations with the Least Sustainable Access to Improved/Clean Water Sources*. Retrieved May 2013, from Africa Public Health Info: http://www.who.int/pmnch/media/news/2012/201205_africa_scorecard.pdf

Pape, J. W., Verdier, R.-I., Boncy, M., Boncy, J., & Johnson, W. D. (1994). Cyclospora Infection in Adults Infected with HIV: Clinical Manifestations, Treatment, and Prophylaxis. *Ann Intern Med. , 121* (9).

Racaniello, V. (2009, July 6). *Detecting viruses: The plaque assay*. Retrieved June 25, 2013, from Virology Blog: http://www.virology.ws/2009/07/06/detecting-viruses-the-plaque-assay/

Sillankorva, S., Kropinski, A. M., & Azeredo, J. (2012). Genome Sequence of the Broad-Host-Range Pseudomonas Phage phiS1. *Journal of Virology , 86* (18), 10239.

Spahl, R. J. (2012). *Groundbreaking Measurement of Free Chlorine Disinfecting Power in a Handheld Instrument*. White Paper, Myron L Company, Oceanside.

The World Bank. (2013). *Haiti Overview*. Retrieved May 2013, from http://www.worldbank.org/en/country/haiti/overview

The World Bank. (2012, July 12). *Haiti: UN's Paul Farmer Stresses Need to Build Systems that Break Cycles of Poverty*. Retrieved July 2, 2013, from The World Bank: http://www.worldbank.org/en/news/feature/2012/07/13/haiti-uns-paul-farmer-stresses-need-to-build-systems-that-break-cycles-of-poverty

Tikkanen, M. W., Schroeter, J. H., Leong, L. Y., & Ganesh, R. (2001). *Guidance Manual for the Disposal of Chlorinated Water*. AWWA.

UN. (2013). *Haiti: Country Profile*. Retrieved June 26, 2013, from International Human Development Indicators: http://hdrstats.undp.org/en/countries/profiles/HTI.html

UN. (2013). *Human Development Index (HDI)*. Retrieved July 5, 2013, from Human Development Reports: http://hdr.undp.org/en/statistics/hdi/

UN. (2012 November 2). *OCHA*. Retrieved July 10, 2013 from Haiti: Hundreds of thousands of people affected by Hurricane Sandy: http://www.unocha.org/top-stories/all-stories/haiti-hundreds-thousands-people-affected-hurricane-sandy

UNICEF. (2013). *Access to water and sanitation: a few definitions*. Retrieved June 28, 2013 from http://www.unicef.org/wcaro/overview_2570.html

UNICEF. (2012, May 26). *Children and water: Global statistics*. Retrieved May 2013, from Water, Sanitation and Hygiene: http://www.unicef.org/wash/index_31600.html

United Nations. (2010). *The Human Right to Water and Sanitation*. Retrieved May 2013, from Water Decade Programme on Advocacy and Communication and Water Supply and Sanitation Collaborative Council: http://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf

USGS. (2013, May 28). *USGS 03335500 Wabash River at Lafayette, IN*. Retrieved June 24, 2013, from National Water Information System: Web Interface: http://waterdata.usgs.gov/usa/nwis/uv?03335500

Van Zyl, N. (2001). *Sodium Hypoclorite Generation for Household Water Disinfection in Haiti*. Thesis, MIT, Civil and Evironmental Engineering.

Weaver, W., Blatchley, E., Wen, Y., & Johnston, J. (2009). Volatile disinfection by-product analysis from chlorinated indoor swimming pools. *Water Res. , 43* (13), 3308-3318.

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

Weinberg, H., Krasner, S., Richardson, S., & Thruston, A. D. (2002). *The Occurrence of Disinfection By-Products (DBPs) of Health Concern in Drinking Water: Results of a Nationwide DBP Occurence Study*. EPA.

Weng, S., Li, J., & Blatchley, E. R. (2012). Effects of UV254 irradiation on residual chlorine and DBPs in chlorination of model organic-N precursors in swimming pools. *Water Research* (46), 2674-2682.

WHO and UNICEF. (2013). Progress on Sanitation and Drinking Water - 2013 Update. US.

WHO. (2012, July). *Cholora*. Retrieved May 2013, from World Health Organization: http://www.who.int/mediacentre/factsheets/fs107/en/

WHO. (2013). *Combating Waterborne Disease at the Household Level*.

WHO. (2000). Global Water Supply and Sanitation Assessment Report. US.

WHO. (2006). *Guidelines for Drinking-water Quality*. WHO Press.

WHO. (2008). Guidelines for Drinking-water Quality. *1*(3). Geneva.

WHO. (n.d.). *Protozoan Parasites (Cryptosporidium, Giardia, Cyclospora*. Retrieved July 5, 2013 from http://www.who.int/water_sanitation_health/dwq/admicrob5.pdf

WHO. (2013). *Water Quality and Health Strategy*. Retrieved May 2013, from World Health Organization: http://www.who.int/water_sanitation_health/publications/2013/water_quality_strategy.pdf

APPENDICES

APPENDIX A. GAGE HEIGHT AND DISCHARGE

The detailed gage height and discharge measurements throughout the course of the experiment, as explained in section 4.1.1, are displayed in Table 10 (USGS, 2013).

Table 10: Gage height and discharge data.

Date	Gage Height (ft)	Discharge (cfs)
12-Mar	13.62	23300
13-Mar	13.37	22800
14-Mar	11.84	19200
15-Mar	9.43	14100
18-Mar	7.17	9360
19-Mar	6.65	8360
20-Mar	6.21	7190
21-Mar	5.55	6390
26-Mar	4.73	5210
27-Mar	4.48	5000
28-Mar	4.47	4850
29-Mar	4.75	5220
1-Apr	6.98	9020
2-Apr	6.46	7900
3-Apr	5.33	6310
4-Apr	4.96	5530
8-Apr	3.98	4090
9-Apr	3.85	3990
10-Apr	4.09	4070
11-Apr	4.04	4230
15-Apr	16.27	31300
16-Apr	14.52	26100
17-Apr	13.64	24300
18-Apr	15.33	28100
1-May	15.51	28800
2-May	15.21	27900
6-May	12.16	20100
7-May	11.38	18300
8-May	10.97	17100
13-May	7.44	9800
14-May	6.67	8390
15-May	5.7	6770

APPENDIX B. FLOW RATE

The detailed flow rate measurements for each string filter throughout the course of the experiment, as explained in section 4.1.2, are shown in Table 11.

Table 11: Flow rate measurements in each filter (mL/s).

	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)	1 µm (stdev)	5 µm (stdev)
14-Mar	13.04	13.14	13.47	14.36	10.26	14.36	13.22	12.99	0.2244	2.3700
15-Mar	13.89	13.19	13.06	12.92	12.92	14.44	13.38	13.43	0.4465	0.8821
18-Mar	12.50	12.25	13.90	13.54	13.40	10.20	12.88	12.38	0.8875	1.8878
19-Mar	13.80	12.70	13.80	13.73	12.42	13.04	13.43	13.06	0.6351	0.6509
20-Mar	11.78	12.70	12.70	12.20	12.00	15.00	12.39	13.07	0.5299	1.6773
21-Mar	11.60	11.57	12.40	13.80	13.40	13.30	11.86	13.50	0.4712	0.2646
26-Mar	14.31	11.68	13.76	13.9	12.2	12.42	13.25	12.84	1.3873	0.9236
27-Mar	12.63	10.69	13.27	12.93	12.43	13.06	12.20	12.81	1.3422	0.3345
28-Mar	12.60	11.88	13.16	13.40	12.00	11.00	12.55	12.13	0.6426	1.2055
29-Mar	14.30	13.80	13.33	12.90	15.70	11.86	13.81	13.49	0.4834	1.9828
1-Apr	13.47	13.54	14.00	13.47	12.48	11.94	13.67	12.63	0.2892	0.7766
2-Apr	13.65	13.27	14.46	13.74	11.55	12.18	13.79	12.49	0.6069	1.1277
3-Apr	12.72	13.13	13.43	13.20	12.42	11.63	13.09	12.42	0.3593	0.7837
4-Apr	13.33	11.80	12.53	13.74	12.42	13.43	12.55	13.20	0.7670	0.6876
8-Apr	11.11	13.20	12.12	13.64	12.08	11.37	12.14	12.36	1.0446	1.1582
9-Apr	13.43	12.44	13.54	12.73	12.45	11.54	13.13	12.24	0.6064	0.6221
10-Apr	12.57	12.83	12.93	13.39	12.04	12.16	12.78	12.53	0.1845	0.7494
11-Apr	13.62	12.62	13.40	13.33	11.98	12.28	13.21	12.53	0.5250	0.7112
15-Apr	12.80	12.62	13.24	13.10	11.71	11.86	12.88	12.23	0.3177	0.7608
16-Apr	12.59	12.80	12.75	12.30	10.19	11.86	12.71	11.45	0.1075	1.1134
17-Apr	13.37	12.63	13.13	12.06	12.16	12.83	13.04	12.35	0.3782	0.4188
18-Apr	13.88	13.11	13.80	12.72	11.70	11.84	13.60	12.09	0.4264	0.5510
1-May	12.53	13.88	12.70	12.28	13.08	12.08	13.03	12.48	0.7355	0.5319
2-May	12.31	11.94	13.73	11.20	12.45	12.32	12.66	11.99	0.9433	0.6883
6-May	12.00	12.80	13.56	13.80	12.57	11.08	12.79	12.48	0.7822	1.3630
7-May	13.03	12.08	12.80	13.27	12.30	12.32	12.64	12.63	0.4962	0.5519
8-May	12.31	10.89	11.80	14.62	11.78	12.04	11.67	12.81	0.7177	1.5664
13-May	12.87	12.52	13.30	13.76	11.67	11.58	12.90	12.34	0.3886	1.2345
14-May	13.43	12.45	12.45	13.54	11.67	11.17	12.78	12.12	0.5660	1.2491
15-May	11.40	12.55	11.27	12.18	10.98	11.18	11.74	11.45	0.7012	0.6425

Table 12 shows the results of the independent-samples t-test performed on the string filter flow rates for the two filter types. With a sample size of three for both filter types, the df value was 4, and the t-value, above which the samples could be considered to be more that 5% different, was 2.7765.

Table 12: T-test results for flow rate measurements.

	T-value	Difference?
14-Mar	0.1648	no
15-Mar	-0.0811	no
18-Mar	0.4206	no
19-Mar	0.7053	no
20-Mar	-0.6623	no
21-Mar	-5.2686	yes
26-Mar	0.4278	no
27-Mar	-0.7620	no
28-Mar	0.5259	no
29-Mar	0.2756	no
1-Apr	2.1746	no
2-Apr	1.7639	no
3-Apr	1.3576	no
4-Apr	-1.0859	no
8-Apr	-0.2428	no
9-Apr	1.7857	no
10-Apr	0.5525	no
11-Apr	1.3398	no
15-Apr	1.3831	no
16-Apr	1.9534	no
17-Apr	2.1281	no
18-Apr	3.7516	yes
1-May	1.0578	no
2-May	0.9877	no
6-May	0.3349	no
7-May	0.0147	no
8-May	-1.1525	no
13-May	0.7505	no
14-May	0.8278	no
15-May	0.5424	no

APPENDIX C. *E. COLI*

The results of the quantification of viable *E. coli* in the raw water and the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.3, are shown in Table 13. The results of the quantification of viable *E. coli* in the raw water and the final water samples for each filter during each day of experimentation are shown in Table 14.

Table 13: Viable *E. coli* colonies/100 mL of sample in the raw water and intermediate water samples.

	Raw Water	Intermediate Water Samples					
		1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C
12-Mar	60	0	0	0	0	0	0
13-Mar	uncountable	0	0	0	0	0	0
14-Mar	73.33	0	0	0	0	0	0
15-Mar	116.67	0	0	0	0	0	0
18-Mar	100	0	0	0	0	0	0
19-Mar	106.67	0	0	0	0	0	0
20-Mar	173.33	0	0	0	0	0	0
21-Mar	200.00	0	0	0	0	0	0
26-Mar	40.00	0	0	0	0	0	0
27-Mar	2.50	0	0	0	0	0	0
28-Mar	20.00	0	0	0	0	0	0
29-Mar	40.00	0	0	0	0	0	0
1-Apr	140.00	0	0	0	0	0	0
2-Apr	40.00	0	0	0	0	0	0
3-Apr	140.00	0	0	0	0	0	0
4-Apr	183.33	0	0	0	0	0	0
8-Apr	100.00	0	0	0	0	0	0
9-Apr	53.33	0	0	0	0	0	0
10-Apr	200.00	0	0	0	0	0	0
11-Apr	190.00	0	0	0	0	0	0
15-Apr	143.33	0	0	0	0	0	0
16-Apr	uncountable	0	0	0	0	0	0
17-Apr	30.00	0	0	0	0	0	0
18-Apr	133.33	0	0	0	0	0	0
1-May	126.67	0	0	0	0	0	0
2-May	116.67	0	0	0	0	0	0
6-May	116.67	0	0	0	0	0	0
7-May	103.33	0	0	0	0	1	0
8-May	113.33	0	0	0	0	0	0
13-May	186.67	0	0	0	0	0	0
14-May	230.00	0	0	0	0	0.67	0.67
15-May	110.00	0	0	0	0	1.33	0.67

Table 14: Viable *E. coli* colonies/100 mL of sample in the raw water and final water samples.

	Raw Water	Final Water Samples					
		1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C
12-Mar	60	0	0	0	0	0	0
13-Mar	uncountable	0	0	0	0	0	0
14-Mar	73.33	0	0	0	0	0	0
15-Mar	116.67	0	0	0	0	0	0
18-Mar	100	0	0	0	0	0	0
19-Mar	106.67	0	0	0	0	0	0
20-Mar	173.33	0	0	0	0	0	0
21-Mar	200.00	0	0	0	0	0	0
26-Mar	40.00	0	0	0	0	0	0
27-Mar	2.50	0	0	0	0	0	0
28-Mar	20.00	0	0	0	0	0	0
29-Mar	40.00	0	0	0	0	0	0
1-Apr	140.00	0	0	0	0	0	0
2-Apr	40.00	0	0	0	0	0	0
3-Apr	140.00	0	0	0	0	0	0
4-Apr	183.33	0	0	0	0	0	0
8-Apr	100.00	0	0	0	0	0	0
9-Apr	53.33	0	0	0	0	0	0
10-Apr	200.00	0	0	0	0	0	0
11-Apr	190.00	0	0	0	0	0	0
15-Apr	143.33	0	0	0	0	0	0
16-Apr	uncountable	0	0	0	0	0	0
17-Apr	30.00	0	0	0	0	0	0
18-Apr	133.33	0	0	0	0	0	0
1-May	126.67	0	0	0	0	0	0
2-May	116.67	0	0	0	0	0	0
6-May	116.67	0	0	0	0	0	0
7-May	103.33	0	0	0	0	0	0
8-May	113.33	0	0	0	0	0	0
13-May	186.67	0	0	0	0	0	0
14-May	230.00	0	0	0	0	0	0
15-May	110.00	0	0	0	0	0	0

APPENDIX D. TURBIDITY

The detailed turbidity measurements in the raw water and the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.4, are shown in Table 15. The detailed turbidity measurements in the raw water and the final water samples for each filter during each day of experimentation are shown in Table 16.

Table 15: Turbidity measurements for the raw and intermediate water samples (NTU).

	Raw Water	Intermediate Water Samples							
		1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	79.1	58.5	54.2	90.5	77.2	63.5	63.5	67.73	68.07
13-Mar	78.4	42.3	34.6	49.5	43.2	25.6	57.6	42.13	42.13
14-Mar	67.1	53.3	37.5	72	67	38.5	36	54.27	47.17
15-Mar	57.5	46.1	59.8	100	53.2	72.2	37.1	68.63	54.17
18-Mar	44.1	69.4	50.2	47.7	28.9	23.7	25.3	55.77	25.97
19-Mar	49.3	16.8	17.2	23.7	39.1	33.1	55.3	19.23	42.50
20-Mar	37.5	136	44.3	92	25.6	13.5	14.3	90.77	17.80
21-Mar	39	39.8	28.9	35.1	18.6	11.2	11.4	34.60	13.73
26-Mar	11.9	32.6	29	20.2	27.2	13.3	24.2	27.27	21.57
27-Mar	9.8	13.3	13.6	13.4	9.1	6.8	12.2	13.43	9.37
28-Mar	11	15.7	12.7	12.2	11.8	8.3	8.9	13.53	9.67
29-Mar	10	9.9	16.4	11.5	7.5	6.8	9.5	12.60	7.93
1-Apr	7.5	16.5	12.8	16.8	13.5	8.8	12.4	15.37	11.57
2-Apr	7.4	11.8	13.9	9.7	10	7.2	7	11.80	8.07
3-Apr	31.1	19.8	17	22	12.8	12.6	12.2	19.60	12.53
4-Apr	19	13.3	13.6	15.6	11.1	10	8.8	14.17	9.97
8-Apr	7.8	11.3	14.6	15.5	10.1	11.5	10.8	13.80	10.80
9-Apr	5.6	9.1	8.6	9.6	7.1	6	6	9.10	6.37
10-Apr	10.6	8.3	11.3	13	7.5	7.3	6.6	10.87	7.13
11-Apr	9.4	8.2	7.3	13	9.1	7	7.2	9.50	7.77
15-Apr	210	108	107	131	70	56	64	115.33	63.33
16-Apr	493	89	108	103	70	55	58	100.00	61.00
17-Apr	144	135	136	152	88	76	85	141.00	83.00
18-Apr	89.5	107	120	115	87.4	71.5	70.2	114.00	76.37
1-May	55.1	91.7	96.2	90.7	69.6	70.3	64.2	92.87	68.03
2-May	40.5	73.9	93.6	78.2	98.7	78.4	74.1	81.90	83.73
6-May	64	107	101	95	91.2	74.8	86.9	101.00	84.30
7-May	40.6	62.5	76	67.7	75.9	58.2	63.8	68.73	65.97
8-May	44.7	105.6	101	73.5	99.4	51.6	47.9	93.37	66.30
13-May	57.7	63.5	72.9	86.3	58.8	56.7	69.8	74.23	61.77
14-May	23.7	56.3	36.6	36.9	54.7	39.7	35.8	43.27	43.40
15-May	15	31.2	32.3	39.6	41.3	27	26.8	34.37	31.70

Table 16: Turbidity measurements for the raw and final water samples (NTU).

	Raw Water	Final Water Samples							
		1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	79.1	32.6	29.7	37.2	38.2	34.3	37.8	32.6	29.7
13-Mar	78.4	41.2	37	42.7	40.7	38.6	38.6	41.2	37
14-Mar	67.1	33.6	32.1	35.5	32.5	28.7	28.6	33.6	32.1
15-Mar	57.5	24.8	23.4	26.6	24	20	19.3	24.8	23.4
18-Mar	44.1	22.8	22.7	26.1	17.6	15.3	15.3	22.8	22.7
19-Mar	49.3	18.8	14.5	18	15.4	12.6	11.4	18.8	14.5
20-Mar	37.5	16.7	13.4	17.5	12.2	11.4	10.4	16.7	13.4
21-Mar	39	11.4	8.8	10.5	8.6	7.3	6.9	11.4	8.8
26-Mar	11.9	8.9	5.5	7.2	4.6	4.3	4.4	8.9	5.5
27-Mar	9.8	4.7	3.8	4.7	3.2	3.1	3.3	4.7	3.8
28-Mar	11	4.8	3.3	4.4	3.4	3.1	3	4.8	3.3
29-Mar	10	3.4	2.5	4.1	2.3	2.6	2.4	3.4	2.5
1-Apr	7.5	3.5	2.6	3.2	2.7	2.6	2.6	3.5	2.6
2-Apr	7.4	2.7	2.1	2.6	2	2	2.1	2.7	2.1
3-Apr	31.1	9	6.1	8.5	6.3	5.9	5.4	9	6.1
4-Apr	19	6	4.1	5.6	4.1	3.8	3.6	6	4.1
8-Apr	7.8	2.6	2.5	3.6	3.4	2	2	2.6	2.5
9-Apr	5.6	2.05	1.47	1.86	1.63	1.18	1.17	2.05	1.47
10-Apr	10.6	3.48	2.79	3.8	2.95	2.44	2.31	3.48	2.79
11-Apr	9.4	2.43	2.2	2.37	1.95	1.67	1.72	2.43	2.2
15-Apr	210	101	82	121	64.8	55.4	58.7	101	82
16-Apr	493	44.1	38.9	51.2	30.1	26.1	26.6	44.1	38.9
17-Apr	144	72	67.8	78.8	51.2	41.6	49	72	67.8
18-Apr	89.5	47.6	37.8	56.1	34.2	28.6	27.9	47.6	37.8
1-May	55.1	39.2	37.1	44.9	29.1	29.6	25.5	39.2	37.1
2-May	40.5	29.1	28	20.9	33.6	21.4	20.1	29.1	28
6-May	64	41.3	40.6	34.7	42.1	30.4	29.2	41.3	40.6
7-May	40.6	28.8	26.8	21.8	29.2	19.6	19.3	28.8	26.8
8-May	44.7	30	28.9	20.8	30.4	17.2	18.7	30	28.9
13-May	57.7	21.1	22.9	17.1	25.1	12.4	12.4	21.1	22.9
14-May	23.7	12.9	14	10.2	13.6	7.4	6.7	12.9	14
15-May	15	7.4	7.33	6.32	7.01	3.95	4.45	7.4	7.33

APPENDIX E. FREE CHLORINE RESIDUAL

The detailed free chlorine residual measurements in the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.5, are shown in Table 17.

Table 17: Free chlorine residuals for the intermediate water samples (mg/L as Cl_2).

	Intermediate Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.42	0.65	0.98	1.24	0.74	0.01	0.68	0.66
13-Mar	0.75	1.32	0.85	0.95	0.95	1.56	0.97	1.15
14-Mar	0.95	0.68	1.2	1.66	1.01	0.72	0.94	1.13
15-Mar	0.74	0.91	1.36	0.79	0.68	0.54	1.00	0.67
18-Mar	0.96	0.65	0.51	0.4	0.77	0.48	0.71	0.55
19-Mar	0.6	0.96	0.31	1.2	0.54	0.98	0.62	0.91
20-Mar	1.44	0.3	0.83	0.84	0.31	0.05	0.86	0.40
21-Mar	1.92	0.43	0.34	1.18	0.9	0.24	0.90	0.77
26-Mar	1.04	0.8	0.76	0.31	0.24	0.36	0.87	0.30
27-Mar	0.25	0.3	0.74	0.23	0.14	0.11	0.43	0.16
28-Mar	0.39	0.19	0.48	0.39	0.18	0.21	0.35	0.26
29-Mar	0.27	0.16	0.25	0.26	0.14	0.1	0.23	0.17
1-Apr	0.43	0.42	0.46	0.4	0.2	0.24	0.44	0.28
2-Apr	0.3	0.23	0.45	0.18	0.13	0.11	0.33	0.14
3-Apr	0.59	0.7	0.6	0.43	0.24	0.43	0.63	0.37
4-Apr	0.46	0.35	0.46	0.32	0.22	0.12	0.42	0.22
8-Apr	0.56	0.57	0.56	0.32	0.24	0.23	0.56	0.26
9-Apr	0.41	0.2	0.37	0.14	0.06	0.07	0.33	0.09
10-Apr	0.32	0.31	0.36	0.17	0.16	0.23	0.33	0.19
11-Apr	0.36	0.22	0.39	0.26	0.13	0.1	0.32	0.16
15-Apr	1.66	1.62	1.92	0.85	0.82	0.91	1.73	0.86
16-Apr	1.54	1.64	1.46	0.97	0.75	0.82	1.55	0.85
17-Apr	1.96	1.76	1.96	1.18	1.02	1.06	1.89	1.09
18-Apr	2.02	1.9	1.76	1.32	0.91	0.87	1.89	1.03
1-May	1.24	1.14	1.18	0.81	1.44	1	1.19	1.08
2-May	0.92	1	0.88	1.2	0.82	0.78	0.93	0.93
6-May	1.74	1.5	1.48	1.08	0.86	1	1.57	0.98
7-May	0.96	0.95	0.95	1.26	1.32	1.08	0.95	1.22
8-May	1.32	1.42	0.97	1.18	0.75	0.75	1.24	0.89
13-May	1.08	1.01	1.3	0.99	0.9	1.06	1.13	0.98
14-May	0.96	0.61	0.53	0.64	0.68	0.69	0.70	0.67
15-May	0.62	0.78	0.86	0.55	0.37	0.4	0.75	0.44

The detailed free chlorine residual measurements in the final water samples for each filter during each day of experimentation are shown in Table 18.

Table 18: Free chlorine residuals for the final water samples (mg/L as Cl_2).

	Final Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.5	0.5	0.7	0.95	0.34	0.48	0.57	0.59
13-Mar	0.9	1.04	0.91	0.73	1.12	0.58	0.95	0.81
14-Mar	1.14	0.7	0.52	0.95	0.64	0.21	0.79	0.60
15-Mar	0.78	0.57	0.57	0.66	0.58	0.47	0.64	0.57
18-Mar	0.65	0.53	0.57	0.76	0.46	0.57	0.58	0.60
19-Mar	0.81	0.36	0.53	0.87	0.48	0.31	0.57	0.55
20-Mar	0.56	1.4	0.44	0.46	0.26	0.4	0.80	0.37
21-Mar	0.98	0.28	0.31	0.38	0.31	0.26	0.52	0.32
26-Mar	0.14	0	0.02	0.03	0	0	0.05	0.01
27-Mar	0.46	0.28	0.19	0.43	0.32	0.41	0.31	0.39
28-Mar	0.32	0.1	0.21	0.39	0.18	0.11	0.21	0.23
29-Mar	0.56	0.31	0.36	0.36	0.25	0.25	0.41	0.29
1-Apr	0.16	0.05	0.07	0.2	0.06	0.19	0.09	0.15
2-Apr	0.28	0.13	0.06	0.01	0.02	0.08	0.16	0.04
3-Apr	0.56	0.36	0.39	0.23	0.26	0.32	0.44	0.27
4-Apr	0.17	0.17	0.06	0.07	0.02	0.12	0.13	0.07
8-Apr	0.2	0.04	0.01	0.05	0	0	0.08	0.02
9-Apr	0.19	0.13	0.13	0.1	0.01	0.01	0.15	0.04
10-Apr	0.47	0.42	0.29	0.12	0.14	0.24	0.39	0.17
11-Apr	0.48	0.14	0.21	0.2	0.17	0.18	0.28	0.18
15-Apr	1.4	1.24	1.6	0.81	0.59	0.79	1.41	0.73
16-Apr	0.65	0.6	0.63	0.32	0.24	0.27	0.63	0.28
17-Apr	1.18	0.84	1.2	0.73	0.5	0.59	1.07	0.61
18-Apr	0.93	0.47	0.59	0.56	0.38	0.28	0.66	0.41
1-May	0.49	0.46	0.47	0.23	0.39	0.31	0.47	0.31
2-May	0.97	0.97	0.56	0.44	0.28	0.36	0.83	0.36
6-May	1.24	0.85	0.49	0.65	0.32	0.28	0.86	0.42
7-May	1.24	1.28	0.51	0.87	0.53	0.56	1.01	0.65
8-May	0.85	1.06	0.62	0.67	0.65	0.75	0.84	0.69
13-May	0.35	0.46	0.75	0.23	0.17	0.19	0.52	0.20
14-May	0.42	0.69	0.45	0.27	0.39	0.49	0.52	0.38
15-May	0.46	0.59	0.27	0.45	0.39	0.47	0.44	0.44

APPENDIX F. TOTAL CHLORINE RESIDUAL

The detailed total chlorine residual measurements in the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.5, are shown in Table 19.

Table 19: Total chlorine residuals for the intermediate water samples (mg/L as Cl_2).

	Intermediate Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.8	0.4	1.08	0.99	0.88	0.94	0.76	0.94
13-Mar	1.3	0.9	1.54	1.26	1.06	1.28	1.25	1.20
14-Mar	1.26	1.4	1.82	1.46	1.08	0.72	1.49	1.09
15-Mar	0.88	1.3	1.9	0.76	0.81	0.45	1.36	0.67
18-Mar	1.08	0.83	0.79	0.37	0.46	0.37	0.90	0.40
19-Mar	0.41	0.37	0.47	0.77	0.59	0.76	0.42	0.71
20-Mar	1.94	0.62	1.32	0.42	0.16	0.18	1.29	0.25
21-Mar	0.83	0.58	0.71	0.36	0.29	0.37	0.71	0.34
26-Mar	1.22	1.24	0.95	0.34	0.42	0.47	1.14	0.41
27-Mar	0.58	0.55	0.92	0.27	0.2	0.19	0.68	0.22
28-Mar	0.68	0.53	0.94	0.44	0.27	0.37	0.72	0.36
29-Mar	0.55	0.46	0.59	0.24	0.08	0.16	0.53	0.16
1-Apr	0.4	0.52	0.55	0.56	0.57	0.45	0.49	0.53
2-Apr	0.62	0.48	0.42	0.27	0.11	0.19	0.51	0.19
3-Apr	0.54	0.73	0.87	0.54	0.44	0.32	0.71	0.43
4-Apr	0.5	0.61	0.24	0.32	0.26	0.08	0.45	0.22
8-Apr	0.7	1.12	0.71	0.36	0.34	0.29	0.84	0.33
9-Apr	0.47	0.45	0.28	0.2	0.16	0.13	0.40	0.16
10-Apr	0.52	0.62	0.4	0.23	0.26	0.26	0.51	0.25
11-Apr	0.62	0.48	0.42	0.29	0.3	0.36	0.51	0.32
15-Apr	1.46	1.44	1.88	0.96	0.73	0.88	1.59	0.86
16-Apr	1.48	1.82	1.68	1.1	0.83	0.86	1.66	0.93
17-Apr	2.4	2.4	2.6	1.54	1.3	1.42	2.47	1.42
18-Apr	1.94	2.1	2.1	1.42	1.16	1.18	2.05	1.25
1-May	1.26	1.32	1.28	0.85	0.91	0.81	1.29	0.86
2-May	1.1	1.24	1.12	1.18	0.99	0.97	1.15	1.05
6-May	1.7	1.6	1.4	1.34	1.06	1.22	1.57	1.21
7-May	1.18	1.18	1.01	1.08	0.85	0.96	1.12	0.96
8-May	1.46	1.34	0.98	1.4	0.78	0.67	1.26	0.95
13-May	1.12	1.1	1.24	0.98	0.82	1.01	1.15	0.94
14-May	0.97	0.79	0.67	0.95	0.64	0.66	0.81	0.75
15-May	0.66	0.83	0.75	0.96	0.57	0.56	0.75	0.70

The detailed total chlorine residual measurements in the final water samples for each filter during each day of experimentation are shown in Table 20.

Table 20: Total chlorine residuals for the final water samples (mg/L as Cl_2).

	Final Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.8	0.32	0.73	0.97	0.32	0.7	0.62	0.66
13-Mar	1.04	1.24	1.22	0.8	1.08	0.76	1.17	0.88
14-Mar	0.73	0.75	0.63	0.66	0.63	0.5	0.70	0.60
15-Mar	0.73	0.68	0.81	0.65	0.66	0.6	0.74	0.64
18-Mar	0.48	0.54	0.86	0.73	0.48	0.59	0.63	0.60
19-Mar	0.37	0.33	0.37	0.45	0.42	0.33	0.36	0.40
20-Mar	0.42	1.14	0.44	0.4	0.38	0.42	0.67	0.40
21-Mar	0.57	0.41	0.56	0.23	0.34	0.26	0.51	0.28
26-Mar	0.41	0.14	0.26	0.22	0.14	0.23	0.27	0.20
27-Mar	0.4	0.61	0.49	0.44	0.52	0.47	0.50	0.48
28-Mar	0.56	0.44	0.52	0.33	0.36	0.38	0.51	0.36
29-Mar	0.57	0.4	0.47	0.36	0.41	0.31	0.48	0.36
1-Apr	0.26	0.07	0.18	0.23	0.14	0.31	0.17	0.23
2-Apr	0.32	0.18	0.11	0.1	0.09	0.16	0.20	0.12
3-Apr	0.61	0.48	0.47	0.32	0.27	0.38	0.52	0.32
4-Apr	0.18	0.13	0.13	0.11	0.16	0.22	0.15	0.16
8-Apr	0.26	0.2	0.15	0.21	0.13	0.13	0.20	0.16
9-Apr	0.22	0.16	0.09	0.13	0.05	0.08	0.16	0.09
10-Apr	0.5	0.41	0.44	0.31	0.34	0.39	0.45	0.35
11-Apr	0.42	0.26	0.27	0.32	0.29	0.26	0.32	0.29
15-Apr	1.48	1.24	1.66	1.1	0.86	0.98	1.46	0.98
16-Apr	0.82	0.67	0.75	0.56	0.46	0.46	0.75	0.49
17-Apr	1.34	1.22	1.22	0.99	0.69	0.91	1.26	0.86
18-Apr	0.97	0.67	0.9	0.61	0.58	0.5	0.85	0.56
1-May	0.47	0.44	0.56	0.35	0.33	0.34	0.49	0.34
2-May	0.67	0.63	0.67	0.63	0.51	0.5	0.66	0.55
6-May	0.79	0.65	0.58	0.69	0.55	0.51	0.67	0.58
7-May	0.59	1.1	0.52	0.59	0.42	0.45	0.74	0.49
8-May	0.66	0.7	0.5	0.67	0.44	0.51	0.62	0.54
13-May	0.6	0.68	0.47	0.47	0.3	0.41	0.58	0.39
14-May	0.6	0.54	0.52	0.42	0.4	0.36	0.55	0.39
15-May	0.61	0.56	0.56	0.43	0.47	0.55	0.58	0.48

APPENDIX G. COMBINED CHLORINE RESIDUAL

The detailed combined chlorine residual measurements in the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.5, are shown in Table 21.

Table 21: Combined chlorine residuals for the intermediate water samples (mg/L as Cl_2).

	Intermediate Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.38	0.00	0.10	0.00	0.14	0.93	0.16	0.36
13-Mar	0.55	0.00	0.69	0.31	0.11	0.00	0.41	0.14
14-Mar	0.31	0.72	0.62	0.00	0.07	0.00	0.55	0.02
15-Mar	0.14	0.39	0.54	0.00	0.13	0.00	0.36	0.04
18-Mar	0.12	0.18	0.28	0.00	0.00	0.00	0.19	0.00
19-Mar	0.00	0.00	0.16	0.00	0.05	0.00	0.05	0.02
20-Mar	0.50	0.32	0.49	0.00	0.00	0.13	0.44	0.04
21-Mar	0.00	0.15	0.37	0.00	0.00	0.13	0.17	0.04
26-Mar	0.18	0.44	0.19	0.03	0.18	0.11	0.27	0.11
27-Mar	0.33	0.25	0.18	0.04	0.06	0.08	0.25	0.06
28-Mar	0.29	0.34	0.46	0.05	0.09	0.16	0.36	0.10
29-Mar	0.28	0.30	0.34	0.00	0.00	0.06	0.31	0.02
1-Apr	0.00	0.10	0.09	0.16	0.37	0.21	0.06	0.25
2-Apr	0.32	0.25	0.00	0.09	0.00	0.08	0.19	0.06
3-Apr	0.00	0.03	0.27	0.11	0.20	0.00	0.10	0.10
4-Apr	0.04	0.26	0.00	0.00	0.04	0.00	0.10	0.01
8-Apr	0.14	0.55	0.15	0.04	0.10	0.06	0.28	0.07
9-Apr	0.06	0.25	0.00	0.06	0.10	0.06	0.10	0.07
10-Apr	0.20	0.31	0.04	0.06	0.10	0.03	0.18	0.06
11-Apr	0.26	0.26	0.03	0.03	0.17	0.26	0.18	0.15
15-Apr	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.04
16-Apr	0.00	0.18	0.22	0.13	0.08	0.04	0.13	0.08
17-Apr	0.44	0.64	0.64	0.36	0.28	0.36	0.57	0.33
18-Apr	0.00	0.20	0.34	0.10	0.25	0.31	0.18	0.22
1-May	0.02	0.18	0.10	0.04	0.00	0.00	0.10	0.01
2-May	0.18	0.24	0.24	0.00	0.17	0.19	0.22	0.12
6-May	0.00	0.10	0.00	0.26	0.20	0.22	0.03	0.23
7-May	0.22	0.23	0.06	0.00	0.00	0.00	0.17	0.00
8-May	0.14	0.00	0.01	0.22	0.03	0.00	0.05	0.08
13-May	0.04	0.09	0.00	0.00	0.00	0.00	0.04	0.00
14-May	0.01	0.18	0.14	0.31	0.00	0.00	0.11	0.10
15-May	0.04	0.05	0.00	0.41	0.20	0.16	0.03	0.26

The detailed combined chlorine residual measurements in the final water samples for each filter during each day of experimentation are shown in Table 22.

Table 22: Combined chlorine residuals for the final water samples (mg/L as Cl_2).

	Final Water Samples							
	1 μm A	1 μm B	1 μm C	5 μm A	5 μm B	5 μm C	1 μm (avg)	5 μm (avg)
12-Mar	0.30	0.00	0.03	0.02	0.00	0.22	0.11	0.08
13-Mar	0.14	0.20	0.31	0.07	0.00	0.18	0.22	0.08
14-Mar	0.00	0.05	0.11	0.00	0.00	0.29	0.05	0.10
15-Mar	0.00	0.11	0.24	0.00	0.08	0.13	0.12	0.07
18-Mar	0.00	0.01	0.29	0.00	0.02	0.02	0.10	0.01
19-Mar	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01
20-Mar	0.00	0.00	0.00	0.00	0.12	0.02	0.00	0.05
21-Mar	0.00	0.13	0.25	0.00	0.03	0.00	0.13	0.01
26-Mar	0.27	0.14	0.24	0.19	0.14	0.23	0.22	0.19
27-Mar	0.00	0.33	0.30	0.01	0.20	0.06	0.21	0.09
28-Mar	0.24	0.34	0.31	0.00	0.18	0.27	0.30	0.15
29-Mar	0.01	0.09	0.11	0.00	0.16	0.06	0.07	0.07
1-Apr	0.10	0.02	0.11	0.03	0.08	0.12	0.08	0.08
2-Apr	0.04	0.05	0.05	0.09	0.07	0.08	0.05	0.08
3-Apr	0.05	0.12	0.08	0.09	0.01	0.06	0.08	0.05
4-Apr	0.01	0.00	0.07	0.04	0.14	0.10	0.03	0.09
8-Apr	0.06	0.16	0.14	0.16	0.13	0.13	0.12	0.14
9-Apr	0.03	0.03	0.00	0.03	0.04	0.07	0.02	0.05
10-Apr	0.03	0.00	0.15	0.19	0.20	0.15	0.06	0.18
11-Apr	0.00	0.12	0.06	0.12	0.12	0.08	0.06	0.11
15-Apr	0.08	0.00	0.06	0.29	0.27	0.19	0.05	0.25
16-Apr	0.17	0.07	0.12	0.24	0.22	0.19	0.12	0.22
17-Apr	0.16	0.38	0.02	0.26	0.19	0.32	0.19	0.26
18-Apr	0.04	0.20	0.31	0.05	0.20	0.22	0.18	0.16
1-May	0.00	0.00	0.09	0.12	0.00	0.03	0.03	0.05
2-May	0.00	0.00	0.11	0.19	0.23	0.14	0.04	0.19
6-May	0.00	0.00	0.09	0.04	0.23	0.23	0.03	0.17
7-May	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
8-May	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13-May	0.25	0.22	0.00	0.24	0.13	0.22	0.16	0.20
14-May	0.18	0.00	0.07	0.15	0.01	0.00	0.08	0.05
15-May	0.15	0.00	0.29	0.00	0.08	0.08	0.15	0.05

APPENDIX H. MIMS

The detailed chloroform concentration measurements from MIMS in the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.6, are shown in Table 23.

Table 23: Chloroform concentrations in the intermediate water samples (µg/L).

	Intermediate Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
15-Mar	17.92	15.15	9.41	3.76	0.90	3.58	14.16	2.75
20-Mar	14.66	15.92	14.44	10.90	11.90	11.78	15.01	11.53
26-Mar	8.68	7.86	6.24	5.86	5.70	3.95	7.59	5.17
4-Apr	11.78	18.72	17.66	12.14	8.17	9.24	16.06	9.85
10-Apr	12.74	11.60	12.82	9.91	8.65	8.18	12.39	8.91
17-Apr	12.05	13.17	11.37	9.61	10.47	12.57	12.20	10.88
7-May	20.88	15.14	13.76	15.34	13.08	15.72	16.59	14.71
14-May	28.61	28.59	25.94	37.21	23.12	24.65	27.71	28.33

The detailed chloroform concentration measurements from MIMS in the final water samples for each filter during each day of experimentation are shown in Table 24.

Table 24: Chloroform concentrations in the final water samples (µg/L).

	Final Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
15-Mar	13.08	11.63	18.52	13.15	14.73	14.01	14.41	21.04
20-Mar	17.30	22.73	16.07	17.44	23.61	22.08	18.70	21.04
26-Mar	14.78	7.11	10.27	9.44	6.80	6.67	10.72	7.64
4-Apr	20.60	14.15	17.34	15.42	17.14	19.25	17.37	17.27
10-Apr	14.17	8.65	14.06	11.89	10.89	10.98	12.29	11.25
17-Apr	17.89	11.80	16.10	13.81	14.28	14.71	15.26	14.27
7-May	19.40	17.05	18.40	17.82	18.10	15.89	18.29	17.27
14-May	13.08	11.63	18.52	13.15	14.73	14.01	14.41	21.04

Table 25 shows the results of the independent-samples t-test performed on the final chloroform concentrations for the two filter types. With a sample size of three for both filter types, the df value was 4, and the t-value, above which the samples could be considered to be more that 5% different, was 2.7765.

Table 25: T-test results for chloroform concentration measurements.

	Final Water Samples	
	T-value	Difference?
15-Mar	-3.0880	yes
20-Mar	-0.8478	no
26-Mar	1.2827	no
4-Apr	0.0436	no
10-Apr	0.4890	no
17-Apr	0.5458	no
7-May	1.0447	no
14-May	0.0119	no

APPENDIX I. UV ABSORBANCE 254

The detailed UV Absorbance measurements at 254 nm in the raw water, and the intermediate water samples for each filter during each day of experimentation, as explained in section 4.1.7, are shown in Table 26. The baseline values for each day are also represented, for reference.

Table 26: UV Absorbance values for the raw and intermediate water samples at 254 nm.

	Baseline	Raw Water	Intermediate Water Samples							
			1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.05	0.49	0.55	0.54	0.33	0.26	0.36	0.52	0.47	0.38
13-Mar	0.04	0.65	0.43	0.39	0.48	0.43	0.34	0.52	0.43	0.43
14-Mar	0.05	0.61	0.56	0.43	0.61	0.61	0.42	0.45	0.53	0.50
15-Mar	0.05	0.47	0.42	0.44	0.70	0.54	0.53	0.42	0.52	0.50
18-Mar	0.12	0.40	0.45	0.52	0.44	0.34	0.31	0.43	0.47	0.36
19-Mar	0.06	0.45	0.30	0.40	0.37	0.45	0.43	0.56	0.36	0.48
20-Mar	0.06	0.38	0.72	0.39	0.51	0.35	0.28	0.26	0.54	0.30
21-Mar	0.06	0.29	0.28	0.24	0.26	0.26	0.23	0.23	0.26	0.24
26-Mar	0.05	0.23	0.45	0.37	0.32	0.38	0.30	0.33	0.38	0.34
27-Mar	0.04	0.21	0.24	0.23	0.24	0.23	0.21	0.24	0.24	0.23
28-Mar	0.00	0.21	0.24	0.21	0.25	0.28	0.22	0.22	0.23	0.24
29-Mar	0.06	0.19	0.21	0.24	0.23	0.21	0.23	0.28	0.22	0.24
1-Apr	0.09	0.16	0.23	0.22	0.24	0.24	0.23	0.23	0.23	0.23
2-Apr	0.07	0.16	0.19	0.19	0.18	0.19	0.20	0.18	0.19	0.19
3-Apr	0.07	0.32	0.26	0.26	0.28	0.23	0.23	0.22	0.27	0.23
4-Apr	0.10	0.26	0.24	0.24	0.25	0.22	0.22	0.21	0.24	0.22
8-Apr	0.10	0.15	0.24	0.26	0.23	0.23	0.26	0.25	0.25	0.25
9-Apr	0.10	0.13	0.16	0.17	0.16	0.17	0.16	0.15	0.16	0.16
10-Apr	0.13	0.15	0.16	0.17	0.17	0.15	0.16	0.14	0.17	0.15
11-Apr	0.13	0.14	0.16	0.14	0.16	0.17	0.15	0.15	0.15	0.16
15-Apr	0.08	1.22	0.83	1.07	1.14	0.76	0.68	0.68	1.01	0.71
16-Apr	0.08	1.65	0.76	0.83	0.80	0.61	0.55	0.55	0.80	0.57
17-Apr	0.09	0.94	0.92	0.89	0.98	0.71	0.65	0.69	0.93	0.68
18-Apr	0.09	0.72	0.73	0.76	0.78	0.62	0.56	0.57	0.76	0.58
1-May	0.10	0.56	0.74	0.76	0.74	0.67	0.66	0.63	0.75	0.65
2-May	0.04	0.48	0.61	0.68	0.66	0.73	0.63	0.62	0.65	0.66
6-May	0.09	0.55	0.79	0.82	0.82	0.74	0.67	0.72	0.81	0.71
7-May	0.03	0.47	0.56	0.63	0.63	0.62	0.56	0.60	0.61	0.59
8-May	0.09	0.47	0.66	0.68	0.59	0.68	0.50	0.48	0.64	0.55
13-May	0.07	0.42	0.54	0.60	0.69	0.53	0.55	0.60	0.61	0.56
14-May	0.06	0.33	0.45	0.38	0.38	0.45	0.41	0.38	0.40	0.41
15-May	0.08	0.26	0.32	0.35	0.36	0.46	0.33	0.33	0.34	0.37

The detailed UV Absorbance measurements at 254 nm in the final water samples for each filter during each day of experimentation are shown in Table 27.

Table 27: UV Absorbance values for the final water samples at 254 nm.

	FInal Water Samples							
	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
12-Mar	0.53	0.61	0.36	0.32	0.35	0.67	0.50	0.44
13-Mar	0.40	0.34	0.40	0.40	0.35	0.37	0.38	0.37
14-Mar	0.36	0.34	0.36	0.36	0.30	0.32	0.35	0.33
15-Mar	0.30	0.32	0.30	0.28	0.25	0.25	0.30	0.26
18-Mar	0.23	0.23	0.24	0.20	0.18	0.17	0.23	0.18
19-Mar	0.27	0.23	0.25	0.23	0.22	0.21	0.25	0.22
20-Mar	0.23	0.18	0.23	0.20	0.19	0.19	0.21	0.19
21-Mar	0.18	0.16	0.15	0.17	0.15	0.15	0.16	0.15
26-Mar	0.16	0.13	0.15	0.13	0.13	0.13	0.15	0.13
27-Mar	0.14	0.13	0.14	0.13	0.12	0.13	0.14	0.13
28-Mar	0.14	0.12	0.13	0.13	0.12	0.12	0.13	0.12
29-Mar	0.14	0.13	0.14	0.13	0.12	0.13	0.14	0.13
1-Apr	0.11	0.10	0.11	0.10	0.10	0.10	0.10	0.10
2-Apr	0.11	0.10	0.11	0.10	0.10	0.10	0.10	0.10
3-Apr	0.17	0.14	0.16	0.15	0.15	0.14	0.16	0.14
4-Apr	0.14	0.11	0.13	0.11	0.11	0.11	0.13	0.11
8-Apr	0.09	0.09	0.10	0.09	0.09	0.09	0.09	0.09
9-Apr	0.08	0.07	0.07	0.08	0.07	0.07	0.07	0.07
10-Apr	0.08	0.07	0.08	0.08	0.07	0.07	0.08	0.07
11-Apr	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06
15-Apr	0.91	0.72	1.03	0.64	0.52	0.56	0.89	0.57
16-Apr	0.45	0.42	0.50	0.36	0.32	0.32	0.46	0.33
17-Apr	0.66	0.59	0.68	0.49	0.43	0.48	0.64	0.47
18-Apr	0.47	0.40	0.51	0.39	0.35	0.34	0.46	0.36
1-May	0.43	0.41	0.46	0.36	0.36	0.32	0.43	0.35
2-May	0.39	0.37	0.32	0.40	0.33	0.32	0.36	0.35
6-May	0.43	0.42	0.38	0.44	0.36	0.35	0.41	0.38
7-May	0.37	0.34	0.33	0.37	0.31	0.31	0.34	0.33
8-May	0.36	0.34	0.29	0.36	0.26	0.27	0.33	0.30
13-May	0.30	0.30	0.26	0.32	0.23	0.23	0.28	0.26
14-May	0.25	0.24	0.22	0.25	0.20	0.19	0.23	0.21
15-May	0.19	0.18	0.18	0.19	0.17	0.17	0.18	0.17

Figures 48 and 49 show the scans for each water sample during each day of testing, from 200 nm to 400 nm on April 9th and April 15th, respectively. These dates were just before and after the heavy rain events.

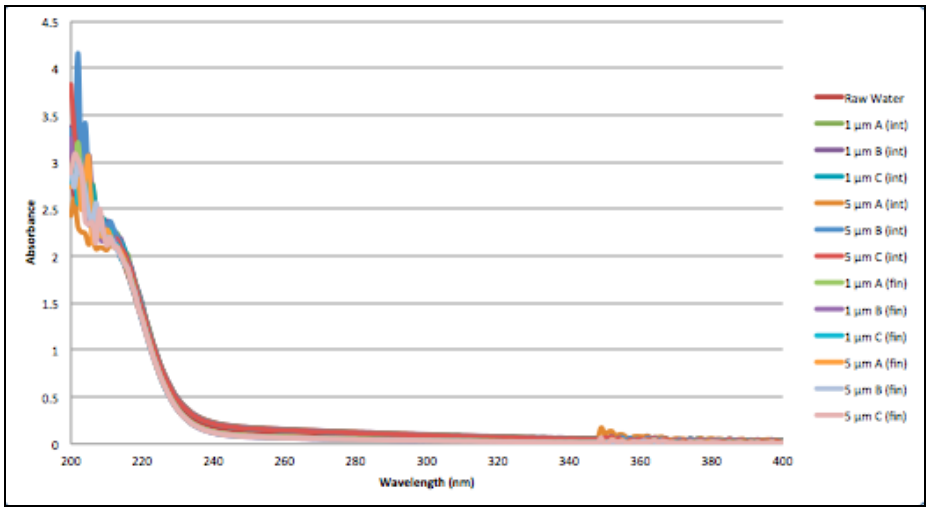

Figure 48: UV Absorbance scan from 400- 200 nm for each water sample on April 9th.

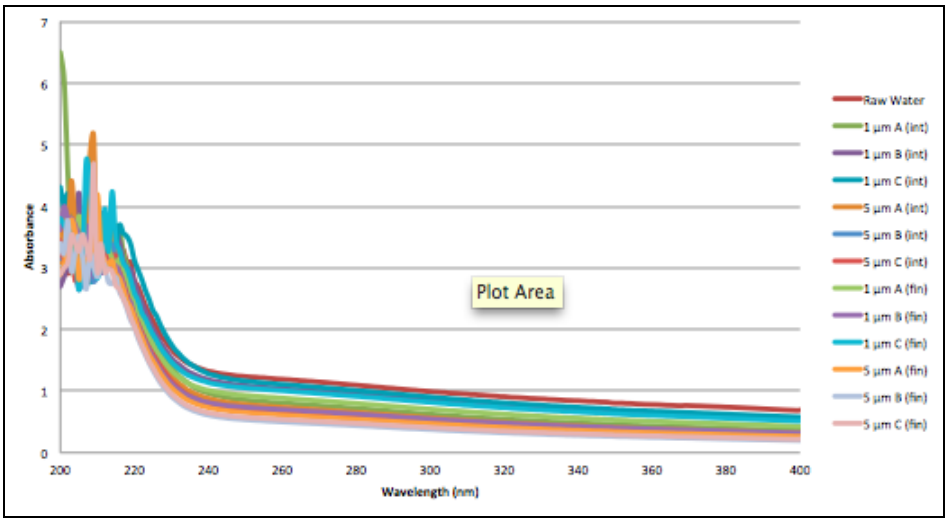

Figure 49: UV Absorbance scan from 400-200 nm for each water sample on April 15th.

APPENDIX J. CLOGGING RATE

Table 28 shows the results for the flowrate measurements in each filter throughout the clogging rate experiment.

Table 28: Flowrates in each filter throughout clogging rate experiment (mL/s).

Date	Time	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
19-Jun	1:30 PM	6.60	12.21	5.10	4.00	10.81	9.90	7.97	8.24
20-Jun	10:30 AM	5.94	11.52	4.80	4.00	10.20	9.41	7.42	7.87
20-Jun	6:30 PM	5.05	15.34	4.81	3.11	9.41	10.10	8.40	7.54
21-Jun	8:15 AM	8.59	9.61	4.46	3.85	9.80	9.80	7.55	7.82
21-Jun	5:00 PM	4.49	9.70	4.91	3.04	9.22	9.80	6.36	7.35
22-Jun	2:00 AM	5.00	3.33	4.86	3.30	8.42	8.69	4.40	6.80
23-Jun	8:15 AM	5.56	8.60	4.95	3.30	5.54	6.73	6.37	5.19
24-Jun	10:00 AM	5.42	5.20	4.55	4.12	6.60	4.24	5.05	4.99
24-Jun	5:40 PM	4.70	5.50	4.00	4.00	3.09	3.43	4.73	3.51
25-Jun	9:00 AM	4.71	5.74	4.59	4.06	2.48	2.77	5.01	3.10
25-Jun	3:45 PM	4.20	3.76	4.36	3.94	5.56	2.12	4.11	3.87
26-Jun	9:00 AM	4.20	2.35	3.96	3.90	1.55	1.73	3.50	2.40
26-Jun	5:15 PM	3.96	4.16	3.33	3.86	3.17	1.88	3.82	2.97
27-Jun	9:30 AM	3.59	2.75	2.82	3.96	2.05	2.18	3.05	2.73
27-Jun	5:30 PM	3.27	2.12	2.91	3.92	1.14	1.27	2.77	2.11
28-Jun	8:00 AM	2.72	2.18	2.67	3.82	1.94	1.83	2.52	2.53
28-Jun	6:00 PM	2.37	1.85	2.37	3.66	1.77	1.80	2.20	2.41
30-Jun	10:15 AM	0.77	0.63	0.71	2.75	5.10	0.81	0.71	2.88
1-Jul	8:30 AM	1.18	1.04	1.26	1.98	1.94	0.97	1.16	1.63
1-Jul	5:00 PM	1.10	0.98	1.50	1.57	1.10	0.99	1.19	1.22
2-Jul	9:15 AM	0.82	0.81	1.47	1.39	0.78	0.60	1.03	0.92
2-Jul	4:45 PM	0.90	1.09	1.72	1.30	1.20	0.67	1.24	1.06
3-Jul	9:00 AM	0.91	1.05	1.57	1.18	1.25	0.75	1.18	1.06
3-Jul	6:00 PM	0.94	1.10	1.52	1.13	1.15	0.78	1.19	1.02

Table 29 shows the results for the cumulative volume filtered through each filter throughout the clogging rate experiment.

Table 29: Cumulative volume filtered through each filter throughout clogging rate experiment (L).

Date	Time	1 µm A	1 µm B	1 µm C	5 µm A	5 µm B	5 µm C	1 µm (avg)	5 µm (avg)
19-Jun	1:30 PM	474	897	374	302	794	730	582	609
20-Jun	10:30 AM	632	1284	513	405	1076	1011	810	831
20-Jun	6:30 PM	970	1901	742	577	1552	1503	1204	1211
21-Jun	8:15 AM	1176	2205	890	686	1851	1812	1423	1450
21-Jun	5:00 PM	1346	2440	1066	800	2169	2145	1617	1704
22-Jun	2:00 AM	1731	2875	1423	1040	2678	2707	2010	2142
23-Jun	8:15 AM	2240	3514	1863	1384	3241	3216	2539	2613
24-Jun	10:00 AM	2379	3662	1981	1496	3374	3321	2674	2731
24-Jun	5:40 PM	2639	3972	2218	1718	3528	3493	2943	2913
25-Jun	9:00 AM	2747	4088	2327	1816	3625	3552	3054	2998
25-Jun	3:45 PM	3008	4278	2585	2059	3846	3672	3290	3192
26-Jun	9:00 AM	3129	4374	2694	2174	3916	3725	3399	3272
26-Jun	5:15 PM	3350	4576	2873	2403	4069	3844	3600	3439
27-Jun	9:30 AM	3449	4646	2956	2517	4115	3894	3684	3508
27-Jun	5:30 PM	3605	4758	3102	2719	4195	3975	3822	3630
28-Jun	8:00 AM	3675	4814	3171	2822	4247	4025	3887	3698
28-Jun	6:00 PM	3903	4994	3395	3286	4744	4214	4097	4082
30-Jun	10:15 AM	3981	5061	3474	3476	5026	4286	4172	4262
1-Jul	8:30 AM	4012	5089	3512	3525	5068	4313	4204	4302
1-Jul	5:00 PM	4068	5142	3599	3611	5123	4359	4270	4364
2-Jul	9:15 AM	4091	5167	3642	3647	5150	4376	4300	4391
2-Jul	4:45 PM	4144	5230	3738	3720	5222	4418	4371	4453
3-Jul	9:00 AM	4174	5264	3788	3757	5261	4443	4409	4487

Table 30 shows the results for the turbidity and TSS measurements in the effluent contact chamber throughout the clogging rate experiment.

Table 30: Turbidity and TSS measurements throughout clogging rate experiment.

Date	Time	Turbidity (NTU)	TSS (mg/L)
19-Jun	1:30 PM	4	5.7
20-Jun	10:30 AM	35	6.2
20-Jun	6:30 PM	1.5	6.2
21-Jun	8:15 AM	2	9.1
21-Jun	5:00 PM	1.8	9.1
22-Jun	2:00 AM	1.78	5
23-Jun	8:15 AM	18.7	3.8
24-Jun	10:00 AM	2.43	3.9
24-Jun	5:40 PM	2.8	3.9
25-Jun	9:00 AM	1.8	3.1
25-Jun	3:45 PM	3.45	3.1
26-Jun	9:00 AM	4.7	4.9
26-Jun	5:15 PM	5.4	4.9
27-Jun	9:30 AM	2.5	4.1
27-Jun	5:30 PM	1.5	4.1
28-Jun	8:00 AM	0.4	5.1
28-Jun	6:00 PM	6.3	5.3
30-Jun	10:15 AM	5.2	4.5
1-Jul	8:30 AM	6.02	4.5
1-Jul	5:00 PM	14.2	4.1
2-Jul	9:15 AM	17.2	4.2
2-Jul	4:45 PM	15.5	4.2
3-Jul	9:00 AM	16.3	4.1
3-Jul	6:00 PM	6.29	4.1

APPENDIX K. INACTIVATION ASSAYS

The results of the inactivation assays for the φS1 bacteriophage suspension with Milli-Q water are shown in Tables 31-33.

Table 31: Plaque assay results for test with φS1 and Milli-Q water.

Run 1	1.60E+08	pfu/mL
Run 2	2.30E+08	pfu/mL
Run 3	1.60E+08	pfu/mL
Average	**1.83E+08**	**pfu/mL**

Table 32: Plaque assay results for test with φS1, sodium thiosulfate and Milli-Q water.

Run 1	2.20E+08	pfu/mL
Run 2	1.60E+08	pfu/mL
Run 3	1.80E+08	pfu/mL
Average	**1.87E+08**	**pfu/mL**

Table 33: Plaque assay results for test with φS1, sodium thiosulfate, free chlorine dose 1 and Milli-Q Water

Run 1	<10	pfu/mL
Run 2	<10	pfu/mL
Run 3	<10	pfu/mL
Average	**<10**	**pfu/mL**

The results of the inactivation assays for the T4 bacteriophage suspension with Milli-Q water are shown in Tables 34-36.

Table 34: Plaque assay results for test with T4 and Milli-Q water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	3.43E+06	2.40E+06	3.00E+06	2.94E+06	pfu/mL
Run 2	3.70E+06	7.00E+06	3.90E+06	4.87E+06	pfu/mL
Run 3	2.98E+06	3.00E+06	3.00E+06	2.99E+06	pfu/mL
			Total Average	**3.60E+06**	**pfu/mL**

Table 35: Plaque assay results for test with T4, sodium thiosulfate and Milli-Q water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	1.00E+05	1.00E+05	1.99E+05	1.33E+05	pfu/mL
Run 3	4.93E+05	1.30E+05	No Data	3.12E+05	pfu/mL
			Total Average	**2.22E+05**	**pfu/mL**

Table 36: Plaque assay results for test with T4, sodium thiosulfate, free chlorine dose 1 and Milli-Q water.

Run 1	7.00E+00	pfu/mL
Run 2	4.00E+00	pfu/mL
Run 3	8.00E+00	pfu/mL
Average	**6.33E+00**	**pfu/mL**

The results of the inactivation assays for the φS1 bacteriophage suspension with Wabash River water are shown in Tables 37-40.

Table 37: Plaque assay results for test with φS1, and Wabash River water.

	Dilution 1	Dilution 2	Average Dilution	pfu/mL
Run 1	3.40E+06	3.01E+06	3.21E+06	pfu/mL
Run 2	2.42E+07	2.60E+07	2.51E+07	pfu/mL
		Average	**1.42E+07**	**pfu/mL**

Table 38: Plaque assay results for test with φS1, sodium thiosulfate and Wabash River water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	2.19E+07	2.80E+07	2.50E+07	2.19E+07	pfu/mL
			Total Average	**2.22E+05**	**pfu/mL**

Table 39: Plaque assay results for φS1, sodium thiosulfate, free chlorine dose 1, and Wabash River water.

Run 1	1.95E+06	pfu/mL
Run 2	2.10E+05	pfu/mL
Run 3	1.00E+04	pfu/mL
Average	**7.23E+05**	**pfu/mL**

Table 40: Plaque assay results for test with φS1, sodium thiosulfate, free chlorine dose 2, and Wabash River water.

	Dilution 1	Dilution 2	Average Dilution	
Run 1	8.40E+02	6.00E+02	7.20E+02	pfu/mL
Run 2	3.50E+04		3.50E+04	pfu/mL
Run 3	1.12E+04	1.50E+04	1.31E+04	pfu/mL
		Total Average	**1.63E+04**	**pfu/mL**

The results of the inactivation assays for the T4 bacteriophage suspension with Wabash River water are shown in Tables 41-44.

Table 41: Plaque assay results for test with T4 and Wabash River water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	4.00E+06	3.50E+06	3.05E+06	3.52E+06	pfu/mL
Run 2	7.00E+06	2.62E+06	3.80E+06	4.47E+06	pfu/mL
Run 3	1.70E+06	1.49E+06		1.60E+06	pfu/mL
			Total Average	**3.20E+06**	**pfu/mL**

Table 42: Plaque assay results for test with T4, sodium thiosulfate and Wabash River water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	3.01E+06	4.90E+06	7.00E+06	4.97E+06	pfu/mL
Run 2	1.90E+06	3.00E+06	2.31E+06	2.40E+06	pfu/mL
Run 3	2.00E+06	2.30E+06	2.26E+06	2.19E+06	pfu/mL
			Total Average	**3.19E+06**	**pfu/mL**

Table 43: Plaque assay results for test with T4, sodium thiosulfate, free chlorine dose 1, and Wabash River water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	2.62E+06	3.40E+06	6.00E+06	4.01E+06	pfu/mL
Run 2	4.00E+06	4.00E+06	3.60E+05	2.79E+06	pfu/mL
Run 3	3.00E+06	3.10E+06	2.84E+06	2.98E+06	pfu/mL
			Total Average	**3.26E+06**	**pfu/mL**

Table 44: Plaque assay results for test with T4, sodium thiosulfate free chlorine dose 2, and Wabash River water.

	Dilution 1	Dilution 2	Dilution 3	Average Dilution	
Run 1	3.00E+05	4.90E+05	5.27E+05	4.39E+05	pfu/mL
Run 2	2.80E+06	2.00E+06		2.40E+06	pfu/mL
Run 3	1.10E+06	8.70E+05		9.85E+05	pfu/mL
			Total Average	**1.27E+06**	**pfu/mL**

Finally, Table 45 shows the inactivation rate constant calculations for the φS1 and T4 bacteriophage suspensions for the first chlorine dose applied in the GOW system, in

Milli-Q water. Table 46 shows the inactivation rate constant calculations for the φS1 and T4 bacteriophage suspensions for both chlorine doses applied in the GOW system, in Wabash River water.

Table 45: Inactivation rate constant calculations for φS1 and T4 in the first chlorine dose with Milli-Q water.

				φS1 bacteriophage suspension		T4 bacteriophage suspension	
	t (min)	Free Chlorine (mg/L as Cl_2)	Ct (mg-min/L)	N_t/N_0	Λ_{CW} (L/mg-min)	N_t/N_0	Λ_{CW} (L/mg-min)
first chlorine dose	0	3.35		5.36E-14	0.51	2.85E-05	0.17
	30	0.67	60.3				

Table 46: Inactivation rate constant calculations for φS1 and T4 in both the first and second chlorine dose with Wabash River water.

				φS1 bacteriophage suspension			T4 bacteriophage suspension		
	t (min)	Free Chlorine (mg/L as Cl_2)	Ct (mg-min/L)	N_t/N_0	Λ_{CW} (L/mg-min)	$\Lambda C_{W(avg)}$ (L/mg-min)	N_t/N_0	Λ_{CW} (L/mg-min)	$\Lambda_{CW(avg)}$ (L/mg-min)
first chlorine dose	0	3.35		0.03	0.08	0.08	1.02	0.00	0.04
	10	0.43	18.9						
	20	0.97	7						
	30	2.5	17.35						
second chlorine dose	0	0.85		0.02	0.09		0.39	0.07	
	10	0.33	5.9						
	20	0.39	3.6						
	30	0.3	3.45						