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Evaluation of Tablet Chlorinator for a Rural Haitian Water Treatment System—Computational Modeling and Laboratory Testing

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EVALUATION OF TABLET CHLORINATOR FOR A RURAL HAITIAN WATER TREATMENT SYSTEM - COMPUTATIONAL MODELING AND LABORATORY TESTING

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ABSTRACT

In today's world, 844 million people lack a basic water service and 2.1 billion lack accessible, readily available, and clean water on the premises of their home (UN-Water, 2018). Data show that rural areas of developing countries like Haiti are far behind the rest of the world when it comes to water, sanitation, and hygiene (WASH) infrastructure (Joint Monitoring Progamme (JMP), 2017a). Treating water in this context comes with many challenges; however, chlorination using calcium hypochlorite tablets proves to be a suitable solution as tablets are effective, inexpensive, and simple to use. Calcium hypochlorite systems have been in service for several years with increasing degrees of success in the municipal water treatment system in the rural village of Cange, Haiti. Since the installation of the newest chlorinator, free chlorine residuals at the water system fountains have met at least the minimum desired level (0.5 mg/L) 69% of the time. This is an increase from only 27% with previous chlorinators but still leaves room for improvement. One theory for why residual chlorine levels fluctuated in the system is that the chlorinator could be producing variable concentrations as the tablets dissolve.

The objective of this work is to characterize the relationship between chlorine tablet dissolution and the hydrodynamics of the chlorinator currently installed in the Cange water system. The effects of flow rate, number of chlorine tablets, and the inlet/outlet location on the chlorinator body were examined with both computational fluid dynamics (CFD) modeling and experiments.

Initial CFD models indicated that the inlet and outlet location played a role in the variation of the chlorinator's effluent concentration and helped to design experiments that

would further investigate this relationship. The effects of varying flow rate and varying number of tablets were also explored. Experiments revealed that there was an elevated chlorine level at the beginning, but usually after about half an hour the concentrations stabilized and remained relatively constant through the end of each seven-hour test. This was true regardless of inlet and outlet location, number of tablets used, or the system flow rate, though it is important to mention that the experiments did not last long enough to let the tablets dissolve below 50% of their initial mass. Data also showed that for the chlorinator setup used in Cange, higher flow rates led to lower effluent concentrations due to dilution, but the mass dissolution rate of the tablet was independent of flow rate. Experiments also show that the concentration of the effluent was proportional to the number of chlorine tablets. Different outlet locations impacted the chlorine concentration dramatically, leading to further CFD analysis to explore how flow patterns affected tablet dissolution. Models with different outlet locations supported the idea that dissolution was affected by the pattern of flow, as experimental results that showed low effluent concentrations were characterized by low flow and eddies in the portion of the chlorinator containing the tablets.

The results from this work suggest that the current chlorination setup used in the Cange water system is effective at providing a constant mass flux of chlorine over time and is likely not a major reason for the variability seen in free chlorine levels at the point of delivery. The knowledge gained here will be useful in designing future upgrades for the Cange system and/or other disinfection systems for resource-constrained communities.

DEDICATION

This work is dedicated to the seven men listed below together known as “Ekip Solid.” The “Solid Team” that keeps the Cange Municipal Water System running day in and day out. Your dedication to the health, safety, and wellbeing of your community is unmatched. Thank you for taking me in and teaching me a little about water and a lot about life.

Yves “Greg” Gracia

Sadrack Louis-Jacques

Gasemy “Kolon” Jules

Robert “Djapanou” Ronald

Vulus “Nol” Nolle

Valmont “Oddjob” Pierre-Louis

Lemandier “Timè” Dieuvert

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No amount of recognition is enough for the hours David Vaughn puts in to working with the students of Clemson Engineers for Developing Countries (CEDC). I am so grateful that he saw potential in me as a young student and encouraged me to follow whatever dreams I set out to accomplish. As a student at Clemson and an intern in Haiti, the opportunities he provided to me were nothing short of life changing.

Thank you to the Episcopal Diocese of Upper South Carolina for their continued backing of CEDC students and the community of Cange. Also, a huge thank you to Fluidtrol Process Technologies for all their support of this project. I think we would be hard pressed to find another company to help design, manufacture, and deliver a chlorinator meant for a system in rural Haiti in less than a week.

I want to acknowledge my family and friends both in the United States and Haiti who have supported me through this journey. I could not have done this without you! Special honor goes to my parents as I would not be where I am today without the sacrifices they have made for me to be here and the constant encouragement they give to me in all areas of life.

Lastly, I would like to acknowledge my Savior, Jesus Christ who is the ultimate provider of all physical and spiritual needs. I am constantly humbled to play a small part of His redemptive work on this Earth and to experience the hope that only He can give.

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1. BACKGROUND

1.1. Water Treatment Globally

Despite being recognized as a human right by the United Nations in 2010, globally 844 million people lack a basic water service and 2.1 billion lack water that is accessible on the premises of their home, available when it is needed, and free from contamination (UN-Water, 2018; United Nations, 2010). Water is not only a human right, but also a necessary resource for nations to meet develop, meet their own goals, and meet the needs of its people. (NSF International et al., 1998). Diarrheal diseases often caused by drinking contaminated water sources are the second leading cause of death worldwide for children between the ages of one month and five years accounting for over half a million deaths in children in 2015 (Liu et al., 2016). Of those lacking access to clean drinking water, most live in developing countries and an estimated 80% live in rural areas (Joint Monitoring Progamme (JMP), 2017b).

The 2030 Agenda for Sustainable Development adapted by all UN Member States in 2015 outlines 17 Sustainable Development Goals (SDGs) and 169 targets that combine action for economic, social, and environmental development in areas of critical importance for humanity and the planet (United Nations, 2015). SDG 6 is to ensure availability and sustainable management of water and sanitation for all and target 6.1 strives to achieve universal and equitable access to safe and affordable drinking water for all by 2030 (United Nations, 2015). This means that water used for drinking, cooking, food preparation, and personal hygiene in households, schools, health facilities, workplaces and public spaces

must be readily available, affordable, and free from pathogens and elevated levels of toxic substances at all times. Inequalities must be overcome for populations subgroups until this is a reality for people of all genders and ages, including those with disabilities (World Health Organization (WHO), 2017).

As a way of monitoring and prioritizing the need for action with this target, five different service levels have been defined as seen in Figure 1 ranging from "no service" where drinking water is collected from some form of surface water to "safely managed" where the water source is located on premises, available when needed, and free from fecal and priority chemical contamination (Joint Monitoring Progamme (JMP), 2017b). Figure 2 shows where we stand globally with 89% of the global population meeting the SDG target of "basic" service.

Service level	Definition
Safely managed	Drinking water from an improved water source which is located on premises, available when needed and free of faecal and priority chemical contamination
Basic	Drinking water from an improved source provided collection time is not more than 30 minutes for a roundtrip including queuing
Limited	Drinking water from an improved source where collection time exceeds over 30 minutes for a roundtrip to collect water, including queuing
Unimproved	Drinking water from an unprotected dug well or unprotected spring
No service	Drinking water collected directly from a river, dam, lake, pond, stream, canal or irrigation channel

Figure 1. Service levels of global drinking water availability
Taken from WHO/UNICEF JMP 2017

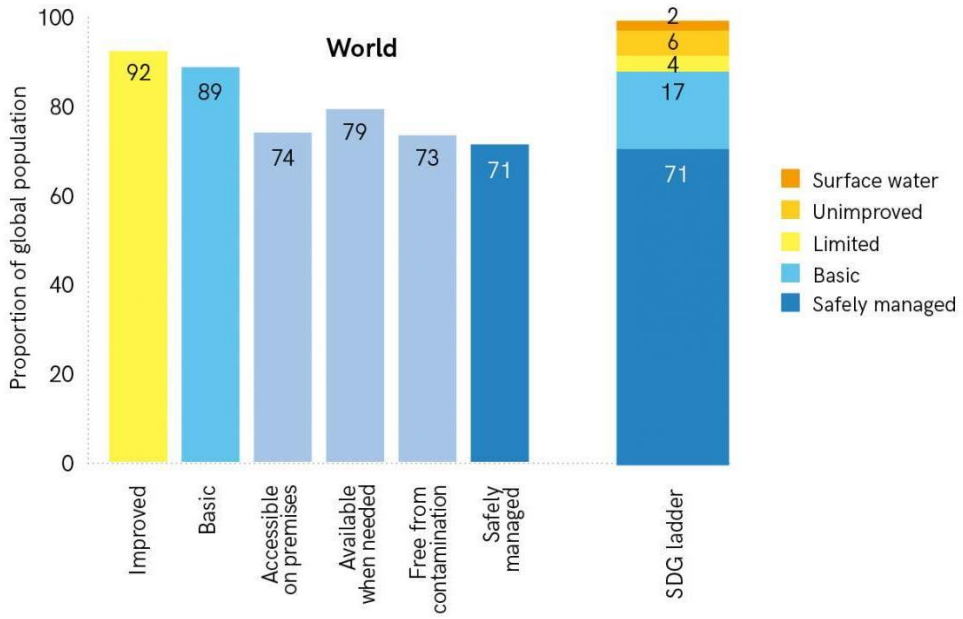

Figure 2. SDG baseline estimates for drinking water services
Taken from WHO/UNICEF JMP 2017

The SDG target stresses improvements in not only quality of water, but also availability and proximity. While it is pretty common knowledge that improved water quality can lead to advances in public health, some argue that increasing quantity can be just as impactful. Increasing water supply encourages better hygiene and hand washing (Curtis et al., 2000). The SDGs also place emphasis on proximity separating a "basic" from "limited" water service based on travel time to the source. Distance traveled to collect water can have many social impacts as well as possibly have a positive correlation to the amount of water present in households (Cassivi et al., 2019). Regardless of which of these factors is most important, making strides towards better quality, quantity, and proximity will result in better public health and becoming closer to meeting the SDG. Another possible benefit of improvements in water and sanitation is financial. A study investigating water and

sanitation improvements in eleven different sub-regions of the world found that all improvements in developing sub-regions were cost-beneficial returning anywhere from $5 to $46 (Hutton et al., 2007). Financial benefits were seen in areas including time savings due to easier access for the user, gain in productive time, and reduced health care costs saved due to less illness and prevented deaths (Hutton et al., 2007).

Since 2000, 1.6 billion people have gained access to basic drinking water services (UNICEF, 2019). Despite major improvements, in 2017, 785 million people still lacked a basic water service and among them 144 million people still collected drinking water directly from rivers, lakes and other surface water sources (UNICEF, 2019). More than one third of countries and only one in five countries below 95% coverage are on track to achieve universal basic water services by 2030 (UN-Water, 2018; World Health Organization (WHO), 2017). When it comes to water resources, these lesser developed countries are falling behind the rest of the world and rural communities are even further behind when compared to urban settings (Hutton et al., 2007; UN-Water, 2018; World Health Organization (WHO), 2017). It is possible that improvements seen in water, sanitation, and hygiene (WASH) globally could be attributed to factors such as urbanization, economic growth and poverty reduction, and rising standards and education rather than actual development efforts (Gordon et al., 2017; Moriarty et al., 2013). Operation and maintenance poses a large challenge to systems in rural, developing environments as often times necessary funds, appropriate support and guidance, limited resources and oversight by government officials lead to poor system performance, high rates of hardware failure, and very low levels of service (Blair et al., 2016; Gordon et al., 2017; Moriarty et al., 2013).

While it can be difficult to estimate actual numbers in this setting, there is a broad consensus that there is a large problem when it comes to non-functionality of rural water supplies (Moriarty et al., 2013). In addition to operation and maintenance challenges, several other constraints affecting the development of the WASH sector have been noted in the literature including inadequate data regarding operation and maintenance, insufficient and inefficient use of funds, poor management of water supply systems, inappropriate system design, inadequate or lacking policies and legal frameworks when it comes to the water and sanitation subsector, and political interference (World Health Organization (WHO), 2003).

1.2. Water Treatment in Haiti

Haiti is a beautiful country located in the Caribbean on the island of Hispaniola along with the Dominican Republic. It was named after the native Taino people's name for the island "Ayiti" (meaning land of high mountains) chosen after a successful slave revolt bought freedom to the people of the island and they wished to connect to the earlier battle of indigenous peoples against the Spanish invaders (Dubois, 2012). Today, Haiti has a population near 11 million and its area is divided into 10 departments shown in Figure 3 (Central Intellegence Agency (CIA), 2020).

Figure 3. Map of Haiti depicting its nine departments
Taken from Geology.com, 2008

Haiti is the poorest country in the Western Hemisphere and has the lowest improved water and sanitation coverage in the Western hemisphere by a large margin. Access to services has not significantly increased for over two decades (Gordon et al., 2017; Patrick et al., 2013; The World Bank, 2020). The latest estimates performed in 2012 indicate that over 6 million people in Haiti live below the poverty line with 2.5 million of those falling below the extreme poverty line of US $1.12 per day (The World Bank, 2020). Rural water and sanitation statistics follow the same trend seen worldwide with decreased access in rural regions shown in Figures 4, 5, and 6. Coverage is drastically lower in rural regions of the country, especially for the poorest population where basic coverage has dropped over

the 17-year span (Joint Monitoring Progamme (JMP), 2017a). Overall in rural areas of Haiti, only 42.6% of people have access to a basic water service compared to 84.7% in urban areas (Joint Monitoring Progamme (JMP), 2017a). The Haitian public water and sanitation authority, Direction Nationale d'Eau Potable et d'Assainissement (DINEPA), has cited many of the same challenges for rural water treatment mentioned in the previous section including a lack of qualified professionals for projects outside of Port-au-Prince, a lack of program monitoring, poor local construction practices, and issues collecting water tariffs in rural areas (Gordon et al., 2017; Hubbard et al., 2014).

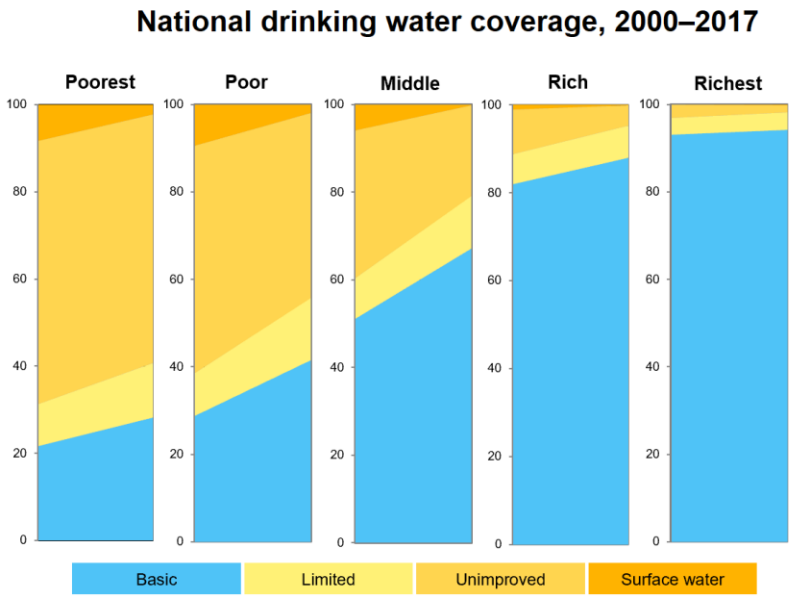

Figure 4. Haiti drinking water coverage change from 2000 to 2017 for different socio-economic groups nationally.
Taken from WHO/UNICEF JMP, 2017

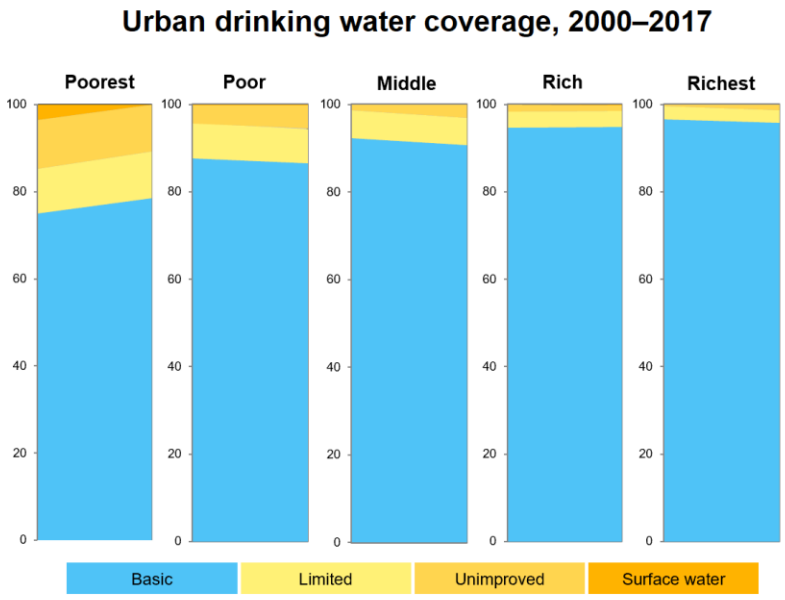

Figure 5. Haiti drinking water coverage change from 2000 to 2017 for different socio-economic groups in urban settings.
Taken from WHO/UNICEF JMP, 2017

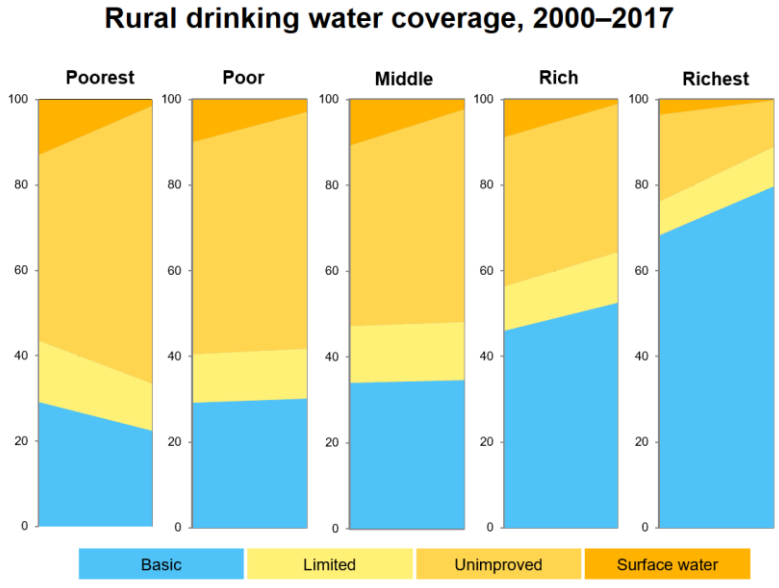

Figure 6. Haiti drinking water coverage change from 2000 to 2017 for different socio-economic groups in rural settings.
Taken from WHO/UNICEF JMP, 2017

Despite lagging behind the rest of its region when it comes to water and sanitation, Haiti has made some positive advances over the last several years (Pan American Health Organization (PAHO), 2020). In 2009, the Haitian parliament unanimously approved a law that aimed to reform the water and sanitation sector completely (Gelting et al., 2013). The new law aimed to do this by giving a renewed focus to the sector and bring on new investment and development plans and also was responsible for the creation of DINEPA (Gelting et al., 2013). The law laid out DINEPA's organization structure, funding, evaluation and control mechanisms and focused on a long-term plan to decentralize water and sanitation services for municipalities (Gelting et al., 2013). Advances in the sector have faced many challenges including political turbulence, unstable availability of financial resources, and vulnerability to natural disasters making sustainable progress difficult (Gelting et al., 2013; The World Bank, 2020).

One clear example of challenges to progress faced by Haiti's WASH sector and an event key to the understanding of the present-day condition of Haiti was the 7.0 magnitude earthquake that rocked Haiti on January 12, 2010. The earthquake killed an estimated 250,000 people, injured at least 300,000 more, and displaced 5 million from their homes (Reid, 2019). The earthquake itself was an unfathomable disaster, but a cholera outbreak followed and was also devastating to a country already lagging in water and sanitation services.

The first cases of cholera were discovered in Haiti in October 2010 in the Central and Artibonite Departments and the disease spread quickly from sewerage to drinking water sources (Pan American Health Organization (PAHO), 2013). Within two months,

cholera cases were present in all departments of Haiti and had effected 170,000 people and killed more than 3,600 by the end of the year (Dowell et al., 2011; Ministere de la Sante Publique et de la Population (MSPP), 2011). By January 15, 2013, three years after the earthquake, the cholera fatality rate was 1.2% which makes this one of the largest cholera epidemics ever recorded in a single country in the world (Pan American Health Organization (PAHO), 2013). The newly formed DINEPA had to rapidly switch focus from long term development to crisis response (Gelting et al., 2013).

Despite the widespread effects of cholera on the country, Haiti actually performed admirably in response to the epidemic (Dowell et al., 2011). Response teams in the field were on location the day that reports of possible cholera cases came in and labs were able to successfully confirm the presence of *V. cholerae* serogroup O1, biotype Ogawa (Tappero & Tauxe, 2011). The outbreak was announced to the public the following day and plans of action were set in place as soon as possible (Tappero & Tauxe, 2011). Response plans included national surveillance, field investigations, laboratory studies, training clinical caregivers and community health workers, working with partners to increase capacity for cholera treatment, improvements in WASH, and educating the public (Tappero & Tauxe, 2011). Through a nationwide surveillance system the epidemic was tracked and cases were reported nearly daily allowing resources to be directed to the areas of greatest need like rural villages and communities where there was a shortage of health care facilities (Dowell et al., 2011; Pan American Health Organization (PAHO), 2013).

Through this response, Haiti slowly overcame the outbreak and saw decreases in case numbers over the past several years (Pan American Health Organization (PAHO),

2018). In January 2020 Haiti celebrated one year free of confirmed cases (Pan American Health Organization (PAHO), 2020). As Haiti gained control over cholera, they were able to focus once again on more of a long term response by building the capacity of local rural water and sanitation technicians, known as TEPACs, that today work in 133 communes across Haiti providing WASH support, assessing water systems, and supporting a community's capacity to monitor free chlorine residuals in their water supply (Centers for Disease Control and Prevention (CDC), 2018).

Overcoming this epidemic was a big success for Haiti, but it is also important to remember that cholera is a disease that is preventable with the technology and knowledge we have today. Despite all the successes of Haiti's response, there were still several challenges that could not be overcome. These challenges included the fact that low sanitation and drinking water coverage provided few barriers to prevent the spread of cholera, the fact that the population had not been exposed to this disease previously, and a lack of needed resources (Tappero & Tauxe, 2011). While the government did a good job communicating the importance of water disinfection, people did not have the means to do so and furthermore, many people in rural areas died at home after being released from overwhelmed hospitals that were over capacity and low on training (Tappero & Tauxe, 2011). The impacts of the earthquake and the following cholera epidemic are a reminder of the challenges faced when the adequate infrastructure and institutions many of us rely on are not present (Dowell et al., 2011). Carissa F. Etienne, a Pan-American Health Organization director, was quoted as saying, "Cholera is a disease of inequity that unduly sickens and kills the poorest and most vulnerable people – those without access to clean

water and sanitation" (Pan American Health Organization (PAHO), 2020). Haiti is subject to many disasters and the lack of clean water and sanitation infrastructure only makes the population even more vulnerable. In order to prevent things like this from happening again, the root issue must be addressed and investments in clean water and sanitation in Haiti must be made.

1.3. The Cange Municipal Water Treatment System

Cange, Haiti is located roughly one and a half hours down National Route #3 from Haiti's capital of Port-au-Prince in a region known as the Central Plateau in the Central Department. The community was formed after the Artibonite River was dammed as part of a hydroelectric project completed by the Army Corps of Engineers in 1956. People were forced to form settlements high in the mountains as the fertile farmland surrounding the river where they once lived was flooded by the formation of Lake Peligre (Kidder, 2003). Cange is a vibrant community consisting of houses, a Zanmi Lasante (Partners in Health) medical complex, a marketplace stretched along the sides of National Route #3, a few restaurants, several churches, schools and homes that stretch across the mountainside.

A brief history of the water system in Cange as described in Gordon et al (2017) begins with a team of engineers from Greenville, South Carolina who traveled to Cange in 1983 to perform a feasibility study for a water system on behalf of the Episcopal Diocese of Upper South Carolina (EDUSC). After a plan was established using a natural

flowing spring at the bottom of the mountain where Cange was located, a hydro-powered pumping system consisting of a dam, penstock, a turbine and piston pump was installed and construction was completed in 1985. The system pumped water without using electricity to the village of Cange around 1000 ft in elevation above the source seen in Figure 7. The people of Cange now had access to drinking water free of charge.

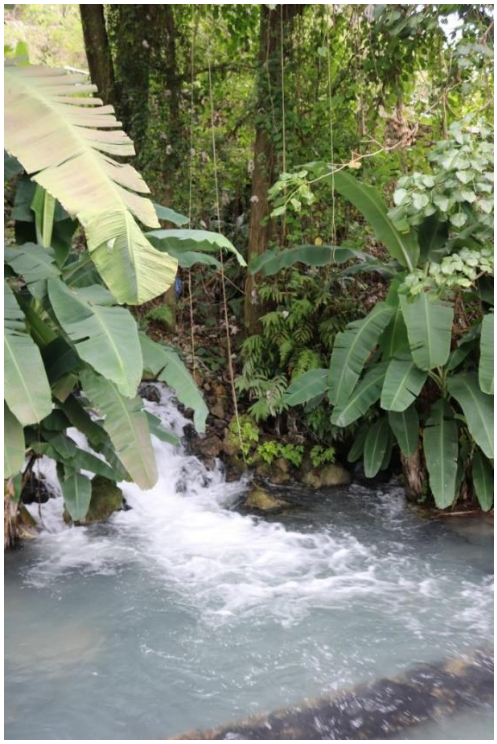

Figure 7. Natural flowing spring located at the bottom of the mountain below Cange. This is the source water for the Cange Municipal Water System.

In 2008, it was determined that parts of the system were approaching the end of their lifespan with the pump wearing out and water threatening to collapse the dam. This is when Clemson students teamed up with industry professionals to form Clemson

Engineers for Developing Countries. The team began creating a plan for updating and improving the system, but when the 2010 earthquake struck, followed by the cholera epidemic, the need for clean water was heightened. The new plan for the Cange water system became constructing a new dam to direct flow into two penstocks, constructing two additional pump houses and installing two additional turbine/piston pumps to meet the demands of the rising population of the region, constructing two additional cisterns, designing and laying a new water line from the pump houses to the cisterns, and designing and implementing a treatment system to purify the water and eliminate the risk of cholera and other water-borne illnesses. Construction for this expansion began in early 2011 and was completed in 2012. In a Haitian news article, the system was highlighted as the Central Plateau's first chlorinated municipal water system (Haiti Libre, 2012). Photos of the different system components are shown in Figures 8-13 as well as an overview of the entire system in Figure 14.

Figure 8. Dam commissioned in 2012 that allowed for system expansion.

Figure 9. Image taken from behind the dam where the water flows into two penstocks that power the turbines.

Figure 10. Example of the inside of one of the pump houses. Water flows through the turbine on the right and powers the piston pump on the left. Water from the turbine is discharged back into the stream outside the pumphouses that flows to Lake Peligre.

Figure 11. Two water storage cisterns. The one on the left was constructed partially underground and the one on the right is located under a hospital dormitory on the Zanmi Lasante compound.

In the most recent census of Cange conducted in 2018, it was reported that around 3,400 people residing in Cange make use of this water system. Water is available to the community several hours a day at eight fountains like the one shown in Figures 12 and 13 and also provides water to the Zanmi Lasante medical complex. It is thought that the number of people using the system could be a few thousand people higher than the population in Cange as people from surrounding villages drive to collect water from the fountains. It is typical for the system to treat over 80,000 gallons per day. Since the project's completion, EDUSC has been financially responsible for the system's operations, maintenance, and upgrades. This has included the purchase of consumable items such as chlorine tablets and oil and grease for the pumps as well as the payment of a team of seven water technicians who are responsible for everyday operations, water quality testing, cleaning, and maintaining the system.

Figure 12. An example of one of the eight fountains located throughout Cange. The fountains have several spigots where water can be collected as well as showers in the rear.

Figure 13. One of the fountains after all eight were painted in 2018 in honor of Pierce and Jackie Williams. Pierce was one of the engineers who designed the original water system and Jackie became a pillar in the community providing English lessons and employing local women in the art center she created.

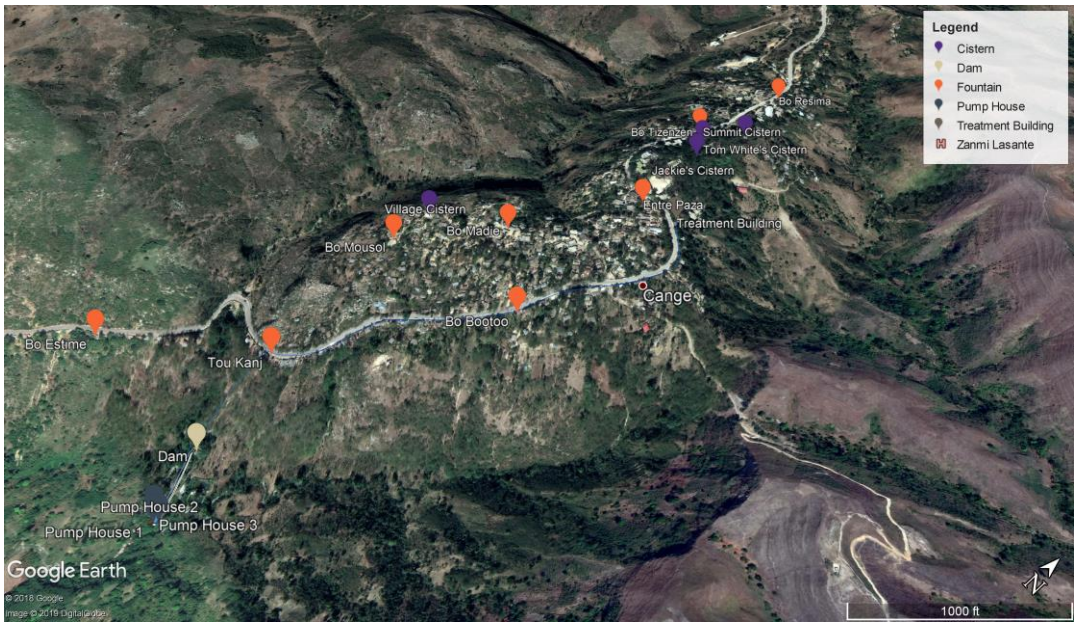

Figure 14. Geographical overview of the Cange Municipal Water System

1.4. Disinfection Using Chlorine

There are many methods to disinfect water in resource-constrained environments that typically fit into two categories: physical and chemical. Physical methods include boiling, ultraviolet radiation, solar water disinfection, and filtration. Chemical methods include chlorine, ozone gas, mixed oxidant gases systems, potassium permanganate, iodine, bromine, and metallic ions such as copper and silver (Haider, 2006). Safety and availability make some of these poor options for developing environments as a good disinfectant should be quick, readily soluble, free from taste, color, and odor, non-toxic, easy to detect and measure, and readily available at moderate cost (Haider, 2006). In an evaluation of many different disinfection techniques in rural water supplies, Haider found that roughing filters supported by chlorine dosing plants for surface water sources and just

chlorination for ground water sources were the most suitable technology for small communities in developing countries (Haider, 2006). Water chlorination combined with filtration seems to be agreed upon as a good option and has been recognized as being potentially the most significant health advancement of the previous millennium (Life, 1997).

Chlorine is the most widely used chemical used for disinfection of water in the United States and has been used for nearly 100 years after Jersey City became the first US city to use calcium hypochlorite for disinfection by continuous chlorination (Harp, 2002; Rivera & Matousek, 2015). Previous work had shown that coagulation and filtration was not enough to reduce microorganisms to safe levels (Crittenden et al., 2012). Within six years of New Jersey's successful use of chlorination systems, 73% of US municipal systems had moved to using the systems as well and as they did, major public health advances were seen including the virtual elimination of typhoid and cholera (Rivera & Matousek, 2015).

Overall, the literature seems to agree that chlorine is a great option for disinfection in resource-limited environments, as well. Technologies such as batch chlorination or flow chlorination are the most frequently used low-cost options (Brikké & Bredero, 2003). The system in Cange has historically used systems with tablets made of calcium hypochlorite to chlorinate the water. These systems provide many benefits including low capital costs and the ability to scale up or down depending on water demand. These types of units are already being used in many applications including being used as the primary disinfection treatment or in remote booster chlorination stations in over forty states (Betcher, 2007).

Additionally, calcium hypochlorite tablet erosion chlorinators and tablets meet many federal requirements including the NSF International standards 60 and 61 for drinking water, American Water Works Association B-300 and several United States Department of Agriculture standards (Betcher, 2007).

Most of chlorine's effectiveness comes from its ability to inactivate a wide range of pathogens and provide a residual against recontamination. To inactive pathogens, chlorine can damage the cell wall, promote leakage through the cell membrane, and produce lower levels of DNA synthesis for bacteria (Meyer, 2004). Chlorine has become such a preferred method of disinfection due to its effectiveness, efficiency, economy of operation, convenience, and the persistence of a chlorine residual (American Water Works Association (AWWA), 2006). There are also potential disadvantages of using chlorine. Chlorination is less effective in alkaline waters, can require pretreatment if there are large amounts of organic matter or suspended materials, and cost and availability can be limiting (Brikké & Bredero, 2003). Taste is another factor when it comes to acceptability. A chlorine taste may be accepted by users as the taste indicates that the water has been disinfected, but if users are not informed, taste may be a reason that people choose to not drink the water or purchase water from somewhere else (Brikké & Bredero, 2003). Despite these limitations, disinfecting water using chlorine is one of the most widely used disinfection practices and is known to use effective, low-cost and low complexity technologies. Disinfection using chlorine should be encouraged especially as it is sometimes the only practical choice for disinfection technologies in certain environments (Brikké & Bredero, 2003; Meyer, 2004).

The efficiency of chlorine disinfection is controlled by several factors including reactor hydraulics, chlorine chemistry, and microbial inactivation kinetics (Greene et al., 2004). In the Cange water system, calcium hypochlorite tablets are used as the disinfectant following filtration. Calcium hypochlorite hydrolyzes according to Equation 1 (Harp, 2002).

$$Ca(OCl)_2\ (s) + 2H_2O\ (l) \rightarrow 2HOCl\ (aq) + Ca(OH)_2\ (aq) \quad (1)$$

Hypochlorous acid (HOCl) is a weak acid and will disassociate according to Equation 2

$$HOCl\ (aq) \leftrightarrow H^+\ (aq) + OCl^-\ (aq) \quad (2)$$

$$pK_a = 7.6 \text{ at } 20°C$$

where hypochlorous acid (HOCl) and hypochlorite ions (OCl^-) are produced (Harp, 2002). These two species are commonly referred to as free available chlorine and in waters with pH between 6.5 and 8.5, the reaction is in equilibrium and both species will be present (Harp, 2002). The hypochlorous acid is more efficient in destroying harmful bacteria due to faster disinfection kinetics so it is crucial to ensure the pH of the water remains in a range that the hypochlorous acid will be present (Crittenden et al., 2012; Harp, 2002; Meyer, 2004).

When chlorine is added to water a series of reactions will occur. The first reaction is with organic matter and metals present in the water that use up some of the disinfecting power of chlorine, converting it to chloride (Centers for Disease Control and Prevention

(CDC), 2014). The amount of chlorine consumed in these reactions is known as the chlorine demand of the water. Chlorine demand can be drastically different for different source waters and can change for one source particularly after heavy rains (World Health Organization (WHO), 2016). The remaining chlorine after the chlorine demand has been met can then be split into two different categories: the chlorine that reacts with nitrates present in the water to form chloramines is called combined chlorine and what is remaining is free chlorine (Centers for Disease Control and Prevention (CDC), 2014). Combined chlorine and free chlorine together are called total chlorine. Both the hypochlorous acid and hypochlorite ions in the solution shown in Equation 2 make up free chlorine (NSF International et al., 1998). Free chlorine is more effective as a disinfecting agent than combined chlorine and so it is the parameter used to determine the potability of water (Centers for Disease Control and Prevention (CDC), 2014; NSF International et al., 1998).

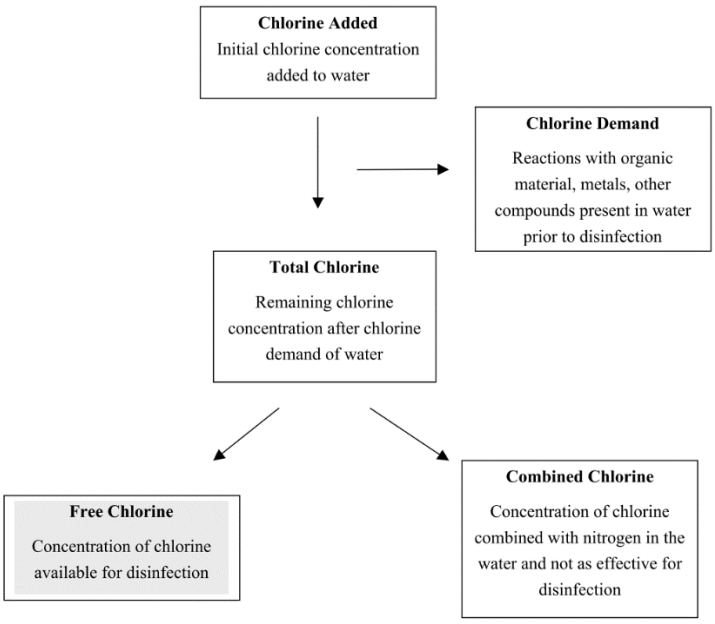

Figure 15. Graphical depiction of chlorine behavior in water. Taken from CDC, 2014

In piped water systems, breakpoint chlorination often occurs where sufficient chlorine must be added to satisfy the chlorine demand and additional chlorine is then used for the purpose of disinfection (World Health Organization (WHO), 2016). Breakpoint chlorination occurs when ammonia is present and reacts with chlorine to form chloramines. The total chloramine concentration (mono- plus di- plus trichloramine) is known as the combined chlorine, as shown in Figure 15 (Crittenden et al., 2012). Following a period of increase, the total chlorine residual begins to decrease once all of the ammonia has reacted with chlorine and their mole ratio is equal causing the additional chlorine added to oxidize the chloramine species (Crittenden et al., 2012). Once all of the chloramines are oxidized, the total chlorine residual begins to increase again at what is known as the "breakpoint" with any increase being free chlorine (Crittenden et al., 2012). An overview of this process is shown in Figure 16.

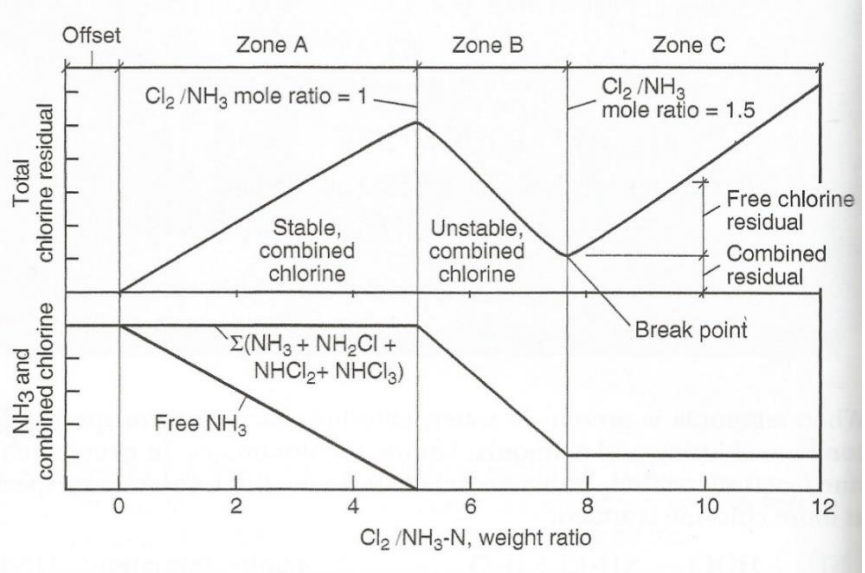

Figure 16. Overview of the processes occurring during breakpoint chlorination. Taken from Crittenden et al., 2012.

A free chlorine residual above a concentration of 0.2 mg/L should be present in drinking water and a maximum concentration of 5 mg/L should not be exceeded for taste and odor reasons (Harp, 2002; World Health Organization (WHO), 1996). In developing countries, there are more factors to consider. In many systems, including the water system in Cange, people rely on filling containers and taking water back to their homes. These additional steps before consumption provide opportunities for recontamination of the water and extend the time between treatment and use. This means that having the correct residual in the water is extra critical and a residual should remain in the water for the average time water is stored in the home which is typically 24 hours (Centers for Disease Control and Prevention (CDC), 2014). A good goal is to see at least 0.2 mg/L of free chlorine after 24 hours (Centers for Disease Control and Prevention (CDC), 2014). Furthermore, where there is a risk of cholera or where an outbreak has occurred, it is recommended that all points in the system have a residual of at least 0.5 mg/L while standposts and wells should have a residual of at least 1.0 mg/L of free chlorine (World Health Organization (WHO), 2016). For general operations, a target free chlorine residual of 0.5 mg/L at the fountains of the Cange Water System is used; however, the system needs to be able to adjust whether that be through additional chlorine added to the system or changes in flow rate if threats of waterborne illnesses occur.

Because the Cange system uses an in-line chlorinator, this study focuses on such designs. In the literature are several examples of in-line chlorinator evaluations that have been conducted around the world. In Panama, PVC pipe chlorinators were tested using varying numbers of tablets to calculate the Ct (concentration * time) value for disinfection.

and comparing this value to the Ct value needed to inactivate common pathogens found in gravity-flow water systems in the developing world (Orner et al., 2017). The chlorinator consisted of a small tube that holds chlorine tablets above the pipe with primary flow and introduces chlorine through a small hole. The chlorinator was found to be capable of reaching the required Ct value required for inactivation of *E. coli*, *Salmonella typhi*, *Vibrio cholerae*, Hepatitis A, Norovirus, and Rotavirus, but not *Giardia lamblia.* Field testing was conducted in Nicaragua for another PVC pipe chlorinator where incoming flow was directed by an influent baffle toward a slotted tube containing a stack of chlorine tablets that dissolved in the flow (Taflin, 2006). In Honduras, a study was conducted to determine the effectiveness of using a hypochlorinator with granulated chlorine versus a tablet feeder using chlorine tablets. It was determined that while tablets are more expensive, the tablet feeders were more effective at disinfecting water and required less maintenance, repair, and replenishments of chlorine (Johnson et al., 2005). Another study recorded the challenges and successes of water treatment in the Dominican Republic (Blair et al., 2016). In Bangladesh, a team compared centralized chlorination to household chlorination and found similar results for both methods when promotion visits were occurring (Pickering et al., 2015). After the promotion visits concluded, however, the chlorination levels for household chlorination fell by 50% and households in the compounds using the passive chlorinators were 1.5 times more likely to have detectable total chlorine residual in their stored water meaning automated, decentralized disinfection increased access to clean water (Pickering et al., 2015).

Almost all of these reports came to the conclusion that in order for a project to be successful close collaboration, community acceptance and involvement, feedback and follow-up, and input from the end users are crucial (Blair et al., 2016; Taflin, 2006). One report also made light of the relationship between social networks and technology adaptation stating that households were 50% more likely to adopt the suggested technology after the study compared to before if they had a close relationship with a household within the treatment group (Kremer et al., 2008). Several comments were made in regard to design of chlorination devices as well. Haider noted that for rural water supplies there is a need for more reliable and simple methods of chlorination as well as simplified methods of monitoring and adjusting the chlorine residual (Haider, 2006). Being able to predict the performance and other factors such as the need for chlorine and potential malfunctions is of great importance in chlorinator design and all of this must be taken into consideration with the input of what the users deem as important (Blair et al., 2016; Johnson et al., 2005; World Health Organization (WHO), 2003). In the end, none of the other factors matter if the system is poorly designed and operating inefficiently (World Health Organization (WHO), 2003). Often times in resource constrained environments, designs must follow "best fit" rather than "best practice" to be successful (UN-Water, 2019).

1.5. History of Chlorination in the Cange Municipal Water Treatment System

The Cange water system has seen several iterations of disinfection design. When disinfection was first introduced to the system both ultraviolet (UV) light and chlorine were

used. UV was later deemed too expensive and difficult to continue operating and is no longer used. One of the biggest challenges for this system is that the treatment process occurs under high pressure (around 100 psi) as the head from the pumps at is used to move the water through the treatment process and then on to the cisterns for storage. Treating the water at low pressure would require this head to be lost and additional pumps added to get the water to the top of the mountain. Seeing the addition of a additional pumps as a larger challenge than treating the water at high pressure, solutions have been found that are capable of operating under these conditions.

All the chlorinators described below were implemented in a side stream of the system where only a small portion of the total flow passes through the unit. Following chlorination, the side stream is reconnected with the main flow line and a static mixer in the line mixes the chlorinated water with the unchlorinated water.

The first chlorinator was manufactured by Accu-tab and can be seen in Figure 17. In this system chlorine tablets sat in the upper chamber where water was pumped through and chlorinated and then pumped into the system. The most negative aspect of this method was that the pump required electricity which is not reliable in Haiti; when the electricity was off, water was not being treated.

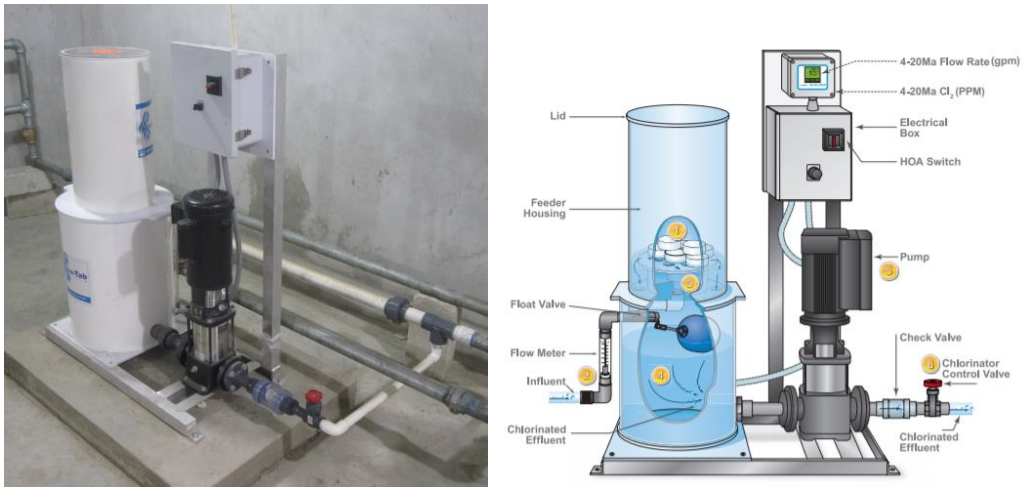

Figure 17. Accu-tab chlorinator

The next design was intended to work without electricity. It consisted of two chambers made from old filter housings with a PVC insert that held the chlorine tablets (Figure 18). The water flowed through the filter housings and the tablets chlorinated the water. The results seen with this method were better than when using the Accu-tab system, but it was difficult to add chlorine tablets to the system because of its design.

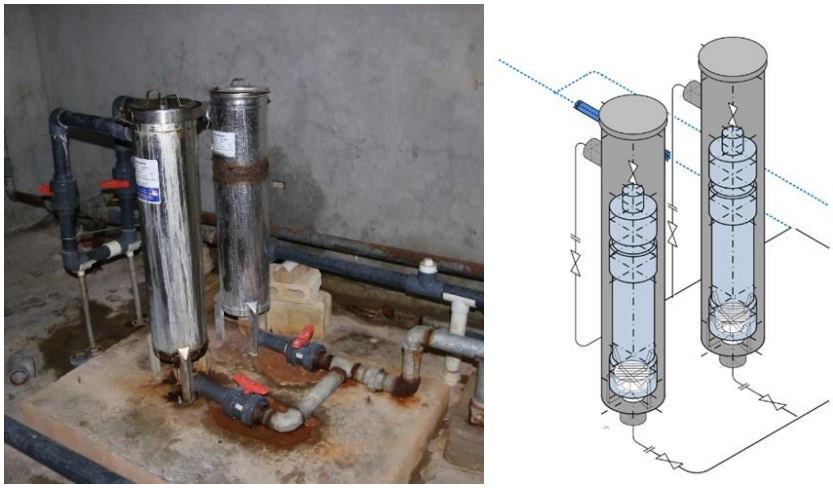
Figure 18. In-line chlorinator made from old system components

The third installation of chlorinators in the Cange water system made use of the same idea as the second, but with a more robust design, seen in Figure 19. The design uses a basket strainer where water flows through a chamber containing a basket holding chlorine tablets. The tablets diffuse into the water effectively chlorinating it. This design was a collaboration between CEDC and Fluidtrol Process Technologies. The results using this design have been the best in the water system's history with free chlorine residual levels meeting at least the minimum desired concentration of 0.5 mg/L much more consistently.

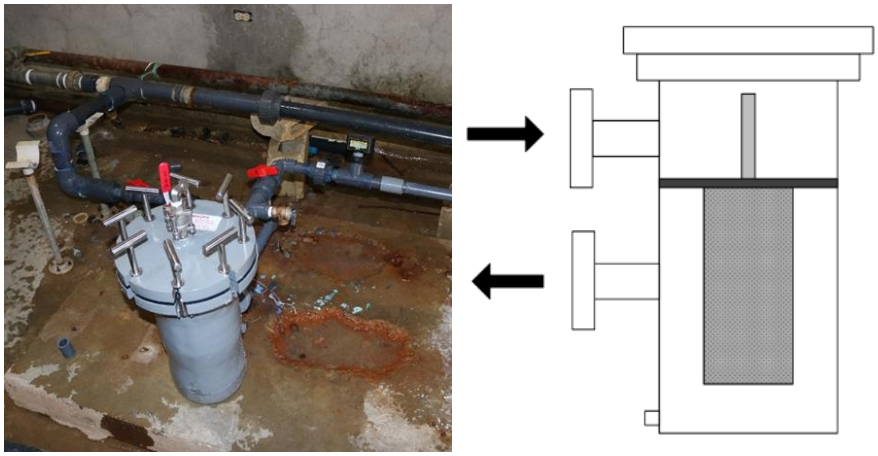

Figure 19. Current chlorinator design

Through experience in Haiti and increased understanding from literature, several parameters have been identified as being crucial for successful chlorination devices in resource-constrained environments as shown in Figure 20. These criteria include ease of operations and maintenance, ability to operate without electricity, delivery of consistent chlorine dose, cost effectiveness, and a robust design.

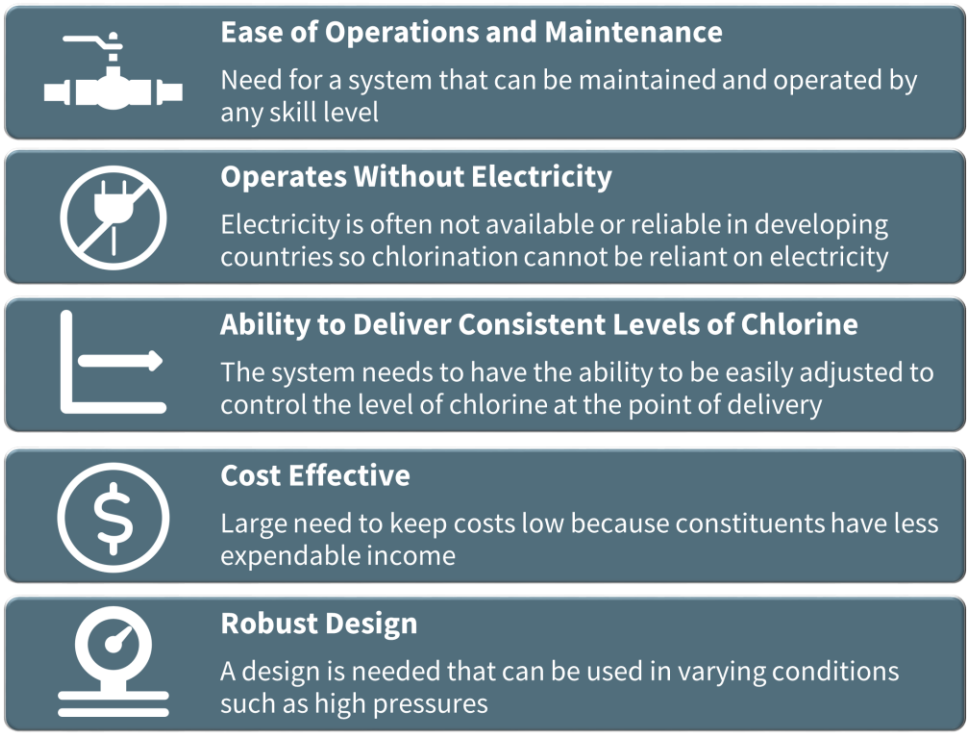

Figure 20. Important parameters to consider when using a chlorination system in a resource constrained environment.

When working in developing environments, the technology must be appropriate and easily understandable so that it can be operated and maintained by someone at any skill level. Operators may not always have a background in water treatment so the form of treatment must be simple enough that it is easily explainable and simple to execute correctly. There are many examples around the world of systems that have failed due to overly complicated or capital-intensive technologies. Operating and maintaining these technologies can quickly become too difficult for the state or local community to handle (Churchill et al., 1987). Technology must be able to be passed to people who live locally and the importance of the need, application and benefits of drinking water treatment must be fully understandable (Meyer, 2004).

Inconsistent or nonexistent electricity often poses a problem for disinfection especially in rural environments. If the grid is unstable it is difficult and unwise to rely on units that require electricity such as pumps or UV lamps. It is important to think about what will happen to the system and quality of water should it lose power.

Whatever method of chlorination is chosen should have the ability to deliver a consistent dose of chlorine to the water resulting in predictable levels of chlorine throughout the distribution system and at the point of delivery. The literature is inconclusive on how effective calcium hypochlorite tablets are at this. One paper states that the effectiveness of chlorine dose control and reliability are not well established when it comes to tablet feeder systems and that it is also possible for non-uniform tablet erosion to affect the overall dosage (Leverenz et al., 2006). However, one manufacturer of calcium hypochlorite tablets claims that the tablets erode at a predictable rate that is dependent upon water flow, so a highly accurate chlorine dosage can be achieved (Betcher, 2007).

The system must be cost effective as this is often a big question when it comes to water treatment in low income environments. Capital as well as maintenance costs should be considered. As mentioned before, it is the consensus in the field that low-cost and simple technology work most effectively in theses settings (Meyer, 2004). While the issue of cost is difficult to analyze due to the variety of water systems and payment structures used, evidence suggests that people in rural areas of developing countries will be able to pay for water and sanitation services (Churchill et al., 1987; World Health Organization (WHO), 2017). Currently, the system in Cange is financially supported by EDUSC, but analysis of system operations and maintenance costs have shown that chlorination using the calcium

hypochlorite tablets are at a low enough cost, along with the total for the rest of the system, that it should not be difficult for the community to support the system for itself should the need arise. In the census completed by CEDC in 2018, many community members stated they are willing and believe they should contribute to the cost of the system.

Lastly, the unit should have a robust design which allows it to operate under any conditions. Because of the way that the Cange Municipal Water System was designed, filtration and chlorination take place under pressures exceeding 100 psi. This is not typical, and most chlorination units are not designed to withstand this type of pressure. Before the most recent chlorinator was installed, another unit with the same design made of schedule 80 PVC was tried in the system. The caps of the unit screwed on and were not strong enough to withstand the pressure of the system. They busted during operation and had to be replaced multiple times before it was accepted that the unit simply was not designed to operate under these extreme pressures. This experience solidified the need for a robust design that would withstand any conditions that may be seen in water treatment systems.

Each of the different chlorination units that have been used in the Cange Municipal Water System have their own pros and cons, which are summarized in Figure 21.

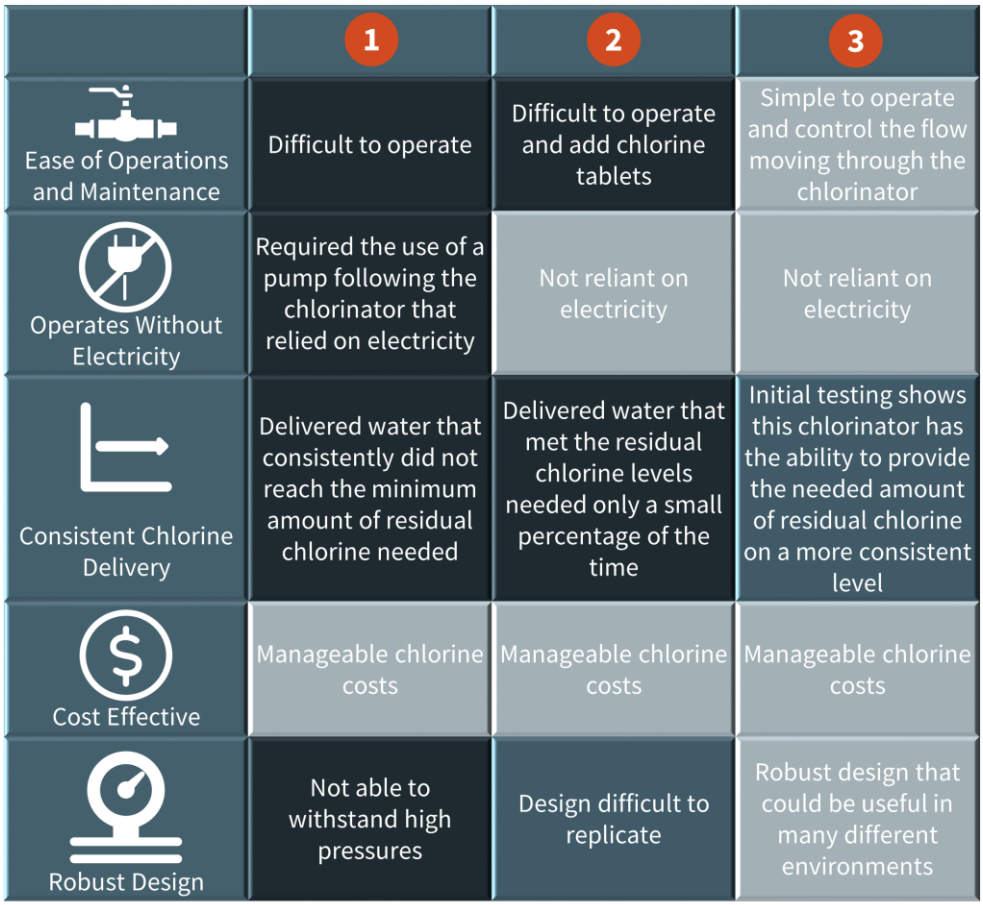

Figure 21. Summary of each chlorination unit used in the Cange Municipal Water System as it pertains to parameters deemed important for successful chlorination. Lighter colors represent better performance for that parameter. System 1 is the Accu-tab chlorinator, System 2 is the in-line chlorinator made from old components, and System 3 is the current tablet chlorinator.

1.6. Water Testing Lab and Field Data Collection

A water testing lab was built on to the water treatment building and completed in 2014. This was the first water testing lab of its kind in the Central Plateau region. The HACH Pocket Pro+ pH Tester and HACH DR900 Multiparameter Portable Colorimeter were purchased to monitor daily water quality and evaluate the levels of free chlorine being delivered at each of the village fountains and within the Zanmi Lasante compound.

Additionally, Coliscan Easygels are used to test for indicator bacteria of fecal contamination of the source water and treated water. A local water technician from Cange was trained to test the water at several different monitoring locations at least three times a week and record the results. He can be seen in Figure 22 at one of the fountains and in Figure 23 testing water in the lab.

Figure 22. Haitian water technician (in orange hat) collects water samples from each fountain of the Cange water system several times a week.

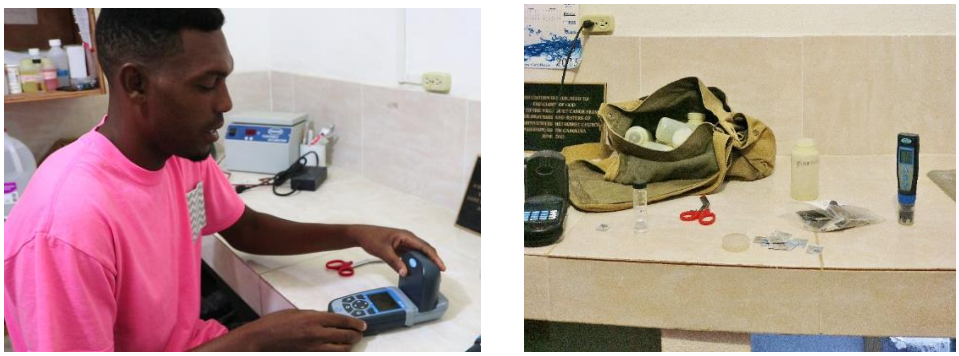

Figure 23. Technician performs water quality measurements in the water testing lab in Cange, Haiti.

1.7. Previous Work in the Field

As a part of this project, I was able to spend ten months living in Cange from October 2017 to July 2018 as a student intern for CEDC. While I was there, I learned about rural water treatment, helped manage the Cange water system, and assisted with WASH projects throughout the Central Plateau. Some of this time was spent digitizing and analyzing water quality data for the Cange water system. For many years, this data was written on paper and stored in envelopes before being carried back to CEDC students for analysis. This worked okay when students came and went between Haiti frequently, but due to Haiti being a high-risk travel country as determined by the U.S. State Department, over time students have not been able to go as frequently. This created a large problem with monitoring the water system as data would not have been seen until months after a problem occurred.

To help with the data monitoring problem, a digital format of the data sheet was created that could be save on a local computer. The folder automatically syncs through Google Cloud and can be seen instantaneously in Clemson as long as there is internet in Cange. The technician can continue saving the data in the folder if there is no internet and when connection is restored, the data will upload to the cloud. The water quality data sheet can be seen in Appendix A. As a part of this work, I created a Python script to combine the datasheets into one table so that it can be more easily analyzed over certain months, seasons, or years. A copy of the script is also located in Appendix A.

I also worked with the local water technician to overcome some of the misunderstandings about chlorination. In an interview I conducted with the technician, it was clear that he understood the importance of having chlorine in the system and the importance of his job for keeping the community healthy and free of illnesses like cholera, giardia, and diarrhea. However, it was also evident that a lot of his knowledge was limited to what he has been told to do when it comes to operation. One misconception he held was that chlorine did not need to be replaced until the chlorine levels were too low at the fountains. This was not a best practice as it is estimated that once leaving the treatment building it takes about 24 hours for water to reach the fountains as storage in the cisterns increases this time before delievery. Another is that you should always use as many tablets as can fit in the chlorinator. Without knowing how the chlorinator is functioning and the effect of using different numbers of tablets, it can't be known for sure that this is the most efficient method of operation.

Before my internship in Haiti, other interns began tracking the chlorine concentrations at the fountains over time when they switched from the Accu-tab chlorinator to the in-line chlorinator made from old system parts in order to try and see any improvements. During my internship, I worked to keep this analysis going as well as update the daily water data sheet to include questions about how much chlorine was being used in the system. The results of the chlorine level tracking over time can be seen in Figure 24 which shows the free chlorine concentration at all of the fountains each day that they were tested.

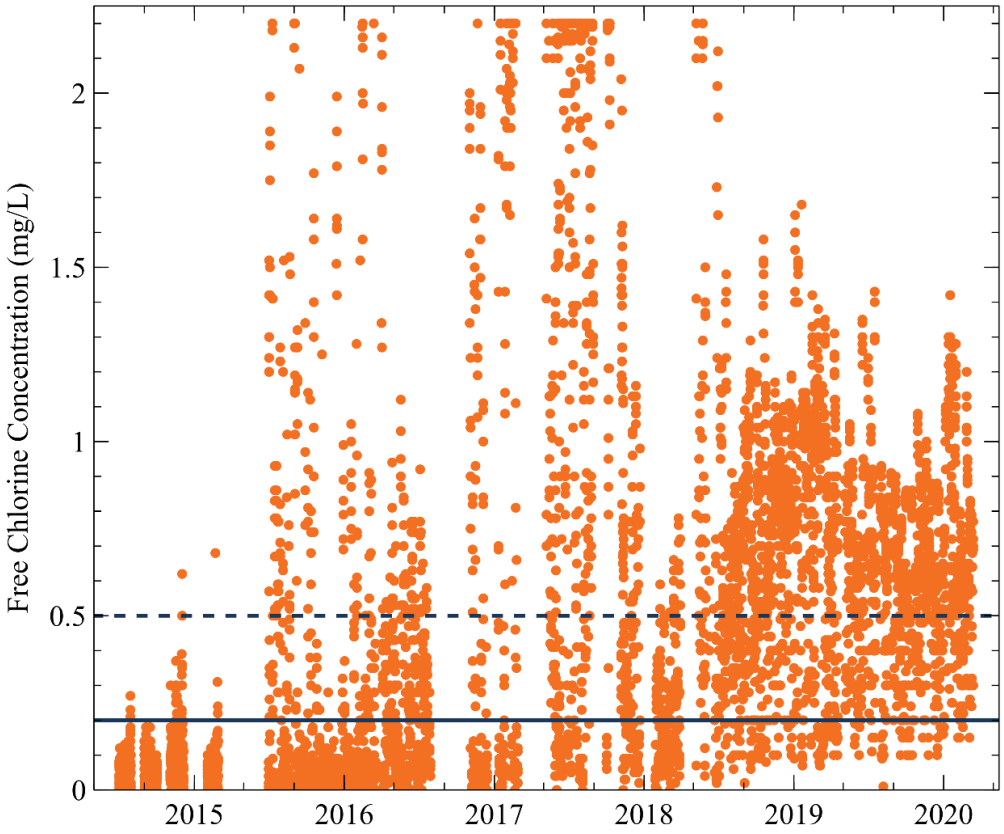

Figure 24. Residual free chlorine measurements at the eight village fountains from July 2014 to March 2020. Each data point on this plot represents a single fountain's free chlorine concentration on that given day.

From this graph, three clusters of data are visible. From July 2014 to mid-2015 it was observed that the free chlorine levels at the fountains were always extremely low providing almost no residual chlorine as people carried the water back to their homes for use. This was the timeframe where the Accu-tab chlorination system was being used which relied on electricity for operation. It became clear that this was not an adequate technology for water disinfection in Cange. A slight improvement was seen after the Accu-tab system was replaced with the old filter housing design shown in Figure 24; however, this setup was difficult to operate and still provided very inconsistent dosages of chlorine with many

days still having too little residual chlorine at the fountains. In March 2018 when the newest tablet feeder erosion chlorinator was installed, an immediate jump can be seen in the data where now a majority of the data points are above the desired level of 0.5 mg/L of free chlorine at the fountains. Further analysis has shown that before this chlorinator was installed, the free chlorine residual was greater than or equal to 0.5 mg/L only 27% of the time. This percentage has increased to 69% with the newest installed chlorinator. Even though the tablet feeder has shown it has the capability needed to provide the desired amount of free chlorine, there is still a large amount of inconsistency in the data. Some days there is not enough residual chlorine at the point of delivery and some days the level is over the amount needed which suggests that the chlorine could be used in a more cost-effective manner.

It is thought that one explanation as to why the level of residual chlorine fluctuates on a daily level at the fountains in the Cange Water System is because of the way that the tablets dissolve inside chlorinator. The design, while simple, does not account for a consistent dosage of chlorine like many other commercially available chlorinators do. This design also differs from most tablet chlorinators in that the tablets are fully submerged. Because there is not consensus on how these tablets operate in the literature and data from the field seemed to support the thought that dissolution of the tablets effects the concentration in the system, further evaluation became the focus of this project.

2. OBJECTIVES AND HYPOTHESES

The overarching goal of this research is to characterize the relationship between chlorine tablet dissolution and the hydrodynamics of the chlorinator system. This goal was accomplished using both computational fluid dynamics (CFD) modeling and experiments to determine the parameters that control the dissolution of the chlorine tablet and the resulting chlorine concentration entering the Cange water system over time. The overarching goal was accomplished through the following specific objectives.

Objective 1: Develop an initial understanding of the chlorinator used in the Cange water system through CFD modeling. Utilize the modeling results from different inlet and outlet locations to design the experiments planned for Objective 2.

*Hypothesis***:** If diffusion and flow velocity at the tablet's surface cause the tablet to dissolve, flow through the chlorinator will cause the chlorine mass transfer rate to decrease as the tablet gets smaller; computational models will show a decreasing effluent concentration over time. Flow patterns that result in the lowest velocities at the tablet surface will have more consistent dissolution as they will mostly rely on diffusion of chlorine from the tablet, which is more consistent than the hydrodynamics.

Objective 2: Learn the effects of different inlet and outlet locations, flow rate, and number of tablets on the effluent concentration over time. Using the initial understanding developed

through the modeling in Objective 1, evaluate chlorinator performance with experiments in a controlled lab setting.

*Hypothesis***:** If the chlorine tablet dissolution is controlled by both diffusion and convection, both flow rate and inlet/outlet location will affect the mass rate of chlorine leaving the chlorinator. Greater number of tablets will lead to higher chlorine concentrations due to the larger exposed surface area for tablet dissolution.

Objective 3: Gain a better understanding of hydrodynamics and chlorine mass transport, beyond what can be ascertained through analysis of the experimental data. Refine the chlorinator CFD models to fit the experimental data from Objective 2 and use the models to investigate factors that could be affecting chlorine concentration.

Hypothesis: If flow patterns through the chlorinator affect the convection of chlorine out of the chlorinator, models that show low flow velocity through the bottom portion of the chlorinator will correspond to the outlet locations that had low chlorine concentrations in Objective 2.

3. MATERIALS AND METHODS

3.1. Objective 1: Initial CFD Modeling

3.1.1. CFD Modeling

To develop an initial understanding of the chlorinator used in the Cange water system, computational models were created using version 5.4 of COMSOL Multiphysics. The purpose of creating the models was to observe the behavior of the chlorinator with no modifications, determine the possible effects that the inlet and outlet location has on performance, and assist in the design of experiments to further explore chlorinator performance. It was hypothesized that due to diffusion and flow velocity at the tablet's surface, the chlorine mass transfer rate would decrease as the tablet gets smaller resulting in a decreasing effluent chlorine concentration over time.

A few examples of computational modeling for chlorination processes were found in the literature and simulate flow structure, mass transport, chlorine decay, and microbial inactivation (Greene et al., 2004, 2006; Hannoun & Boulos, 1997; Wang & A. Falconer, 1998). This study is only looking at flow structure and mass transport and will also differ from these other studies by modeling the dissolution of a chlorine tablet.

3.1.2. Conceptual and Mathematical Model

The important processes in the models will be flow through the chlorinator, the dissolution of chlorine tablets, and the transport of free chlorine in the flowing water within

the chlorinator. It is important to note that these initial models will focus on the general behavior of the chlorine transport and not on the actual values of the chlorine concentration. This will be taken into account later as more knowledge about the diffusion coefficient and surface concentration of the tablet is gained.

For fluid flow through the chlorinator, the conservation of mass and momentum equations are important. The continuity equation for conservation of mass applied to the water is as follows

$$\nabla \cdot (\rho \mathbf{q}) + \frac{\partial \rho}{\partial t} = \mathsf{M} \tag{3}$$

where the first term is the divergence of the mass flux and the second term represents the change in fluid density over time.

The conservation of momentum equation, or Navier-Stokes is as follows

$$\mathbf{F} - \nabla P + \mu \nabla^2 \mathbf{v} = \rho (\nabla \cdot \mathbf{v}) \mathbf{v} + \rho \frac{\partial \mathbf{v}}{\partial t} \tag{4}$$

where F is the body forces, P is the fluid pressure, v is the fluid velocity vector, μ is the kinematic viscosity, and ρ is the fluid density.

The general equation for dissolved mass in fluid will be used to model the mass of chlorine moving through the system. The equation is as follows

$$\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{q}C - D\nabla C) - \mathsf{R} = 0 \tag{5}$$

where the first term represents the rate of change of mass stored, the second term represents the divergence of mass flux where qC is advection and $D\nabla C$ is dispersion, and the third term represents a source.

In these models, a moving mesh was incorporated to represent the dissolution of the tablet. This was accomplished by dividing the density of the tablet by the mass flux from the surface of the tablet which results in the velocity at which the mesh moves.

There are several important boundary conditions and initial conditions that will inform the use of these equations and these will be discussed in the next section.

3.1.3. COMSOL Model

The equations written in the previous section are represented in COMSOL under the Laminar Flow Physics and Transport of Diluted Species Physics. The Laminar Flow Physics built in to COMSOL is used for computing the velocity and pressure fields for a single-phase fluid flowing in the laminar flow regime. While the flow through the chlorinator is turbulent as shown in Appendix B with the calculation of the Reynold's number, laminar flow models take much less computational power and will allow for the models to be run more easily. Since this objective is about gaining an understanding of how the chlorinator is operating, using a laminar flow representation of the chlorinator will operate well enough to serve this purpose with much faster run times. The Transport of Diluted Species Physics computes the concentration field of a dilute solute in a solvent. In these models, this will include the transport of chlorine through the chlorinator to the outlet.

For the models that use a moving mesh to represent the chlorine tablet dissolving, a prescribed normal mesh velocity must be defined. In this case, the prescribed normal mesh velocity is defined as the mass flux from the surface of the tablet divided by the density of the tablet. The value for the tablet density was adjusted until the tablet dissolved at a realistic rate. An example of what the moving mesh looked like in the models can be seen in Figure 25.

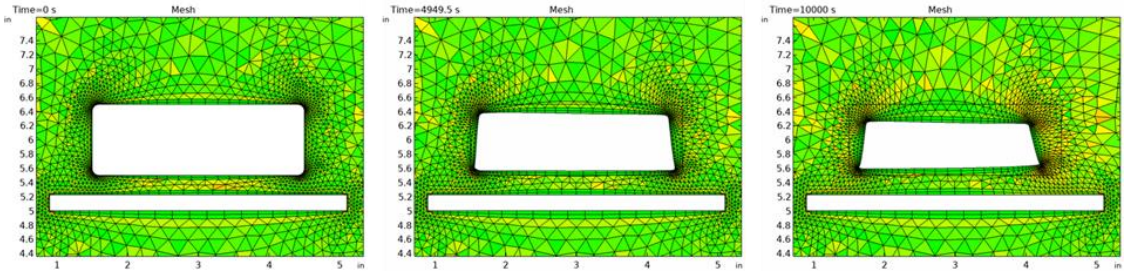

Figure 25. Example of moving mesh created to represent tablet dissolution.

The boundary conditions for the fluid flow physics can be seen in Figure 26. A normal inflow velocity of 0.001 m/s was used at the inlet and an outlet condition of zero pressure was used. All the remaining lines in the geometry were set as no slip boundary conditions.

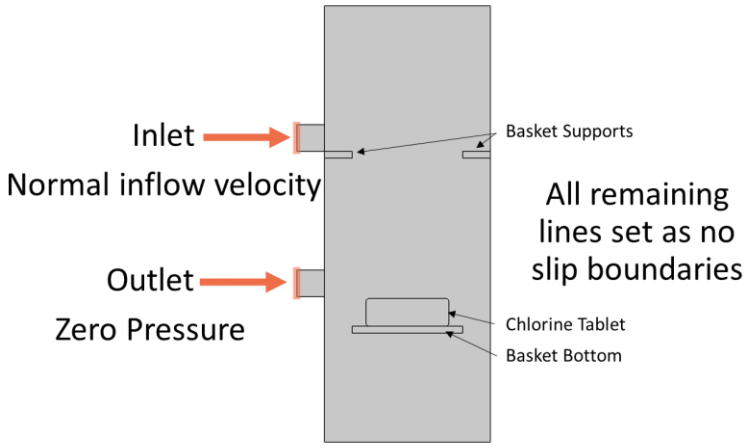

Figure 26. Fluid flow boundary conditions

The boundary conditions for the species transport physics can be seen in Figure 27. A concentration of zero was set as the boundary condition at the inlet and an outflow boundary condition was defined at the outlet. The concentration of the tablet surface was set to 1 mol/m^3 and the initial condition set inside the chlorinator body was a concentration of 0 mol/m^3. All the remaining lines were set as a no flux boundary. The diffusion coefficient was set to 1×10^{-9} m^2/s.

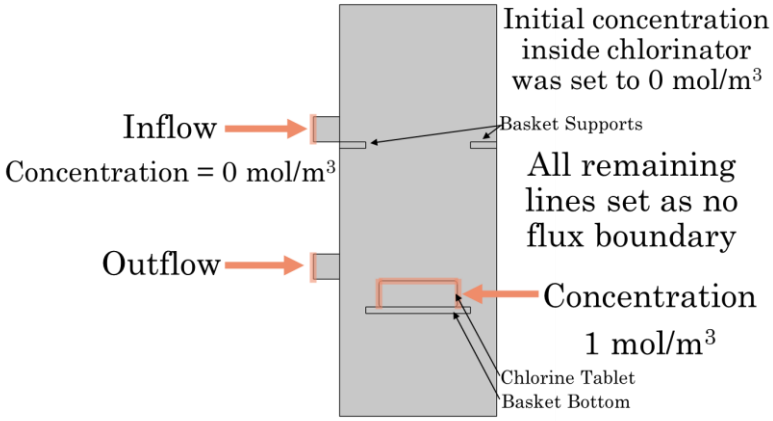

Figure 27. Transport of diluted species boundary conditions

The model geometry was set up for both a 2D and 3D domains as shown in Figures 28 and 29. The sides of the basket that is placed inside the chlorinator to hold the tablets were omitted from the COMSOL designs to simplify the mesh and it was thought that this should not affect the flow patterns.

For the 2D models, a mesh was defined for the models with a maximum element size of 1.06 in and a minimum element size of 0.00473 in. This resulted in a mesh of around 7,000 domain elements and around 525 boundary elements (number varied based on the number of tablets modeled within the chlorinator). For the 3D model, the maximum element size was defined as 1.57 in and the minimum was 0.28 in. This resulted in a mesh consisting of 33,767 domain elements, 4,756 boundary elements, and 661 edge elements.

The maximum element size was reduced to 0.835 for the models with a moving mesh, which resulted in around 10,500 domain elements and 640 boundary elements. The mesh can be seen in Figures 28 and 29. Additionally, Figure 30 shows a closer view of the mesh surrounding the chlorine tablet. An important note is that the corners of the tablet were filleted in order for the mesh to wrap around them and be able to constrict without the model crashing.

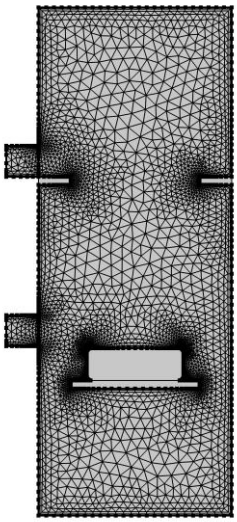

Figure 28. 2D geometry mesh

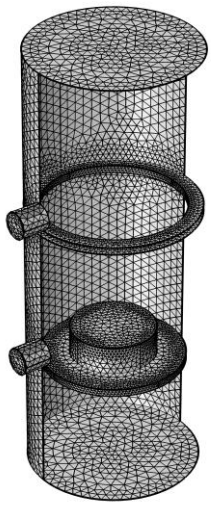

Figure 29. 3D geometry mesh

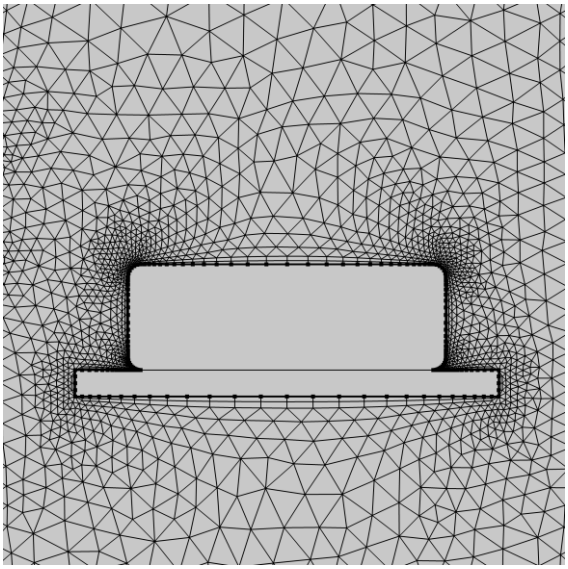

Figure 30. Mesh surrounding chlorine tablet

3.1.4. Model Approach

For these first models, many assumptions were made to keep the models simple. These were sufficient to achieve the first objective of beginning to understand the

chlorinator system while dissolution of the tablet occurred. These initial models were also meant to be sufficient to help design subsequent experiments. Major simplifications included modeling fluid flow as laminar flow and using a flow rate much lower than a realistic value. Overall, these simplifications meant that the model would run for shorter time periods and with greater likelihood that each run would converge on a solution. Another simplification was to make the surface concentration of the tablet equal to 1 mol/m^3. This value was unknown and would have been difficult to determine before taking laboratory measurements. For these first models, just the relative concentrations leaving the chlorinator were evaluated, rather than the absolute values.

For all of the simulations run, two studies were conducted: a stationary and a time-dependent study. The stationary study was run in order for the flow profile to develop inside the chlorinator. The flow results of this study were then used as the starting conditions for the time-dependent study.

3.1.5. Study 1: Comparison of 2D and 3D Model

The first model run was a comparison of the 2D and 3D geometries. The 3D is a more realistic model of the chlorinator, but the 2D was much simpler to run and was less time consuming. Because a many scenarios needed to be analyzed, running 2D models made sense, especially as a starting point; however, it is important to be aware of the differences that exist between the results of the two models. A 2D model and 3D model of the chlorinator were run for a period of around 3 hours each. These models did not use the

moving mesh to model tablet dissolution and just one chlorine tablet was modeled. The time allotted to each model allowed for the development of steady-state chlorine concentration conditions due to the tablet not dissolving.

3.1.6. Study 2: Effect of Various Numbers of Tablets

The next study was conducted to understand the effects of different numbers of tablets in the chlorinator. Because this model used a moving mesh, a few further simplifications had to be made to the model for it to converge. First, the bottom of the tablet had to be raised off the bottom of the basket just a small amount for the model to run and the tablets had to be modeled as one unit instead of multiple tablets. The geometry used for modeling multiple tablets can be seen in Figure 31.

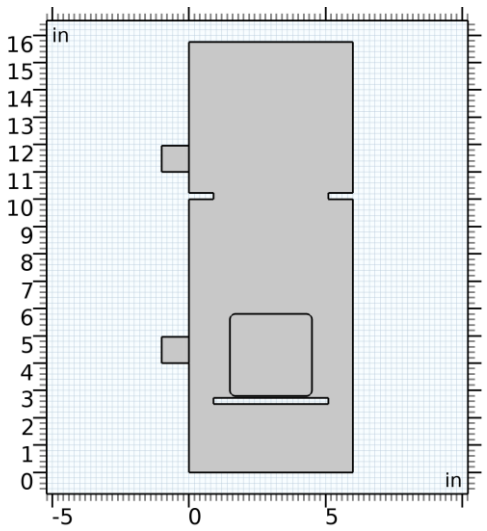

Figure 31. Geometry used for modeling three chlorine tablets.

For this study, the inlet velocity was set to a normal inflow velocity of 0.001 m/s, the surface concentration of the tablet was set to 1 mol/m^3 and the density of the tablet was set to 9 mol/m^3. The time-dependent model was run for a day and a half and the number of chlorine tablets in the chlorinator was modeled at one, three, and five tablets.

3.1.7. Study 3: Effect of Changing Inlet and Outlet Location

The last study conducted was to determine the effects that the location of the inlet and outlet have on the chlorine mass rate leaving the chlorinator. Seven different geometries were run to gain a better understanding of how this component of the design affects the chlorine dissolution.

For this study, the inlet velocity was set to 0.001 m/s, the surface concentration of the tablet was set to 1 mol/m^3 and the density of the tablet was set to 9 mol/m^3. The time-dependent model was run for a day and a half. The different geometries modeled in addition to the actual geometry can be seen in Figure 32.

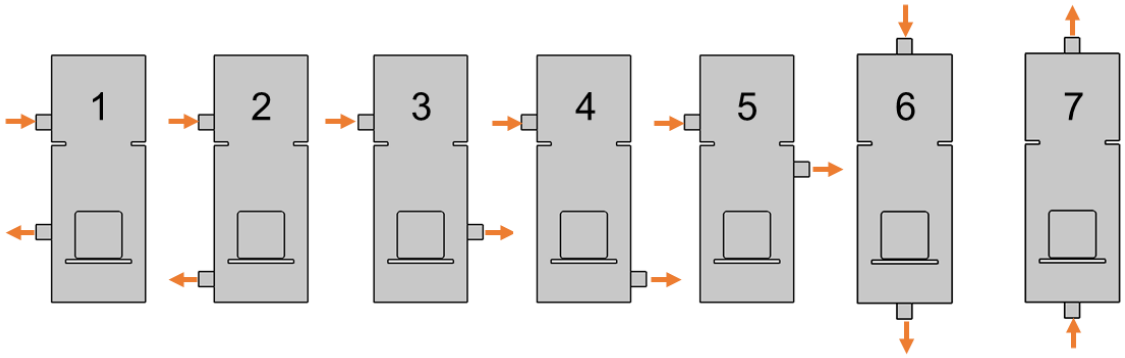

Figure 32. Geometries run with varying inlet and outlet locations

3.2. Objective 2: Experimental Data Collection to Determine Chlorine Tablet Behavior

3.2.1. Experimental Chlorinator Design

A chlorinator very similar to the one used in the Cange Water System was designed with the help of Fluidtrol Process Technologies. The chlorinator design that was used for lab testing includes several different ports to allow for the inlet and outlet to be located at different locations. The chlorinator was also made using all clear materials so that the processes occurring inside could be observed. A photo of the chlorinator can be seen in Figure 33. The design is rated for 50 psi and a pressure meter was added to the top as well as a pressure relief valve. The last addition was a drain at the bottom of the unit.

Figure 33. Experimental chlorinator set up in the lab.

3.2.2. Chlorine Tablets

The same chlorine tablets used in Haiti were used for these experiments. Accu-Tab SI tablets are listed as being safe for drinking water and are manufactured to not soften and clog the system. The tablets are comprised of 65-76% calcium hypochlorite, 10-30% sodium chloride, and small percentages of calcium hydroxide, calcium chlorate, calcium carbonate, pentasodium triphosphate, and calcium chloride (Westlake Chemical & Axiall, 2020). These tablets are marketed as being safe to use, simple, and effective (Axiall Water Treatment Products, 2013).

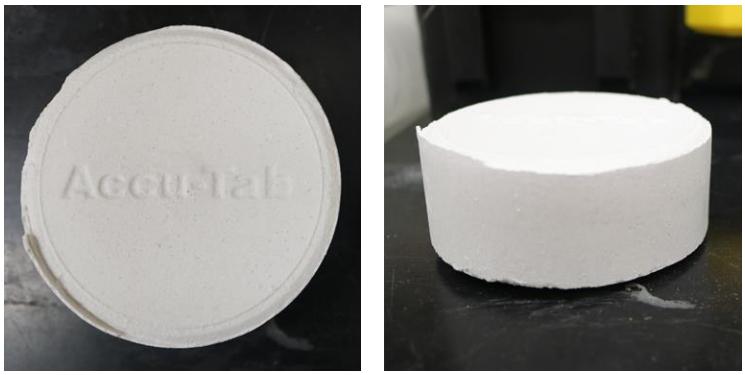

Figure 34. Accu-tab SI tablets top and side view.

3.2.3. Lab Setup

To conduct the experiments, measures were taken to ensure consistent operations. To guarantee the flow rate of the system stayed constant, a flow totalizer was added to the system. This allowed for the volume of water to be divided by the time of the experiment at any point during the experiment to ensure the flow rate had not changed. As another measure of controlling flow, water was kept at a constant head by pumping water from one

tank to a second which had an overflow back to the first tank. Having the overflow on the second tank allowed for the water to stay at that head throughout the entire experiment and kept the flow rate very constant. This setup is shown in Figure 35. Experiments were run in a high-bay laboratory and these holding tanks were on the top floor roughly 15 feet above the chlorinator on the bottom floor. The outlet hose was also kept at a constant elevation using a clamp to attempt to keep the different tests as similar in nature as possible especially when the outlet was moving on the chlorinator.

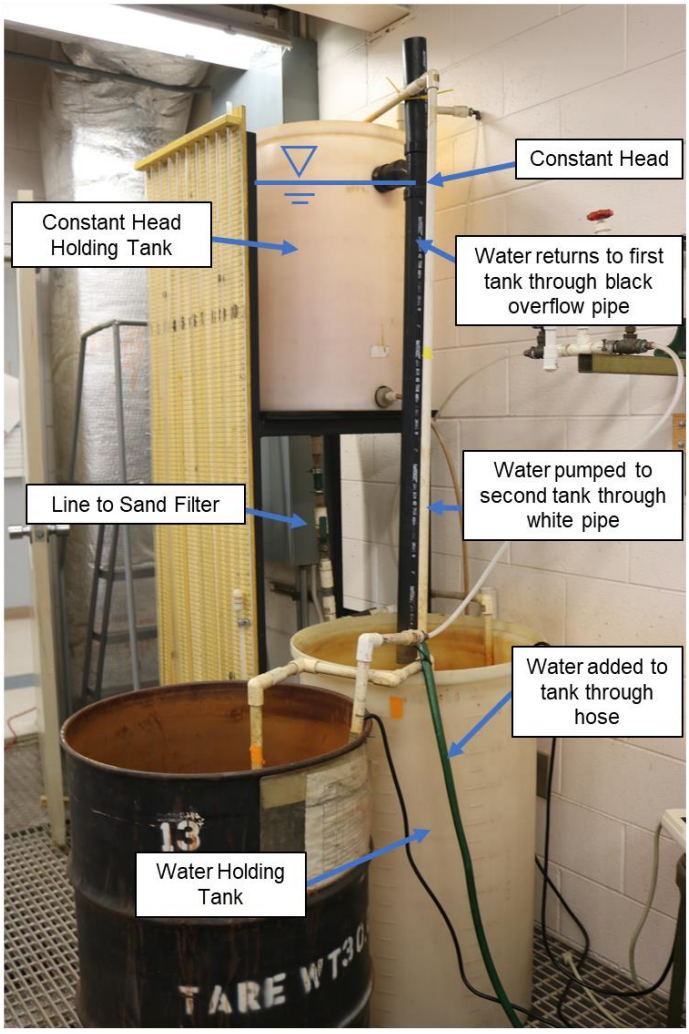

Figure 35. Picture of set-up to keep a constant head and control flow through the chlorinator.

From the second tank, water flowed through a large sand column roughly 20 feet tall. The idea for using the filter was that it could potentially remove residual chlorine from the tap water, however tests during the experiment from the sampling port after the sand column showed this was not the case. The decision to continue using the column was also made due to the fact that it was already connected to the tanks used for the constant head system. The filter potentially removed particulates that had entered the water from the tanks. Figure 36 shows an image of the sand column.

Figure 36. Sand column used during testing.

From the column, the water flowed through tubing to the chlorinator. Using ball valves at the inlets and outlets of the chlorinator allowed for the location to be moved very easily. The ball valves could be left in place and opened or closed as needed and the tubing could screw on to whichever location was desired. A schematic of the entire system is shown in Figure 37.

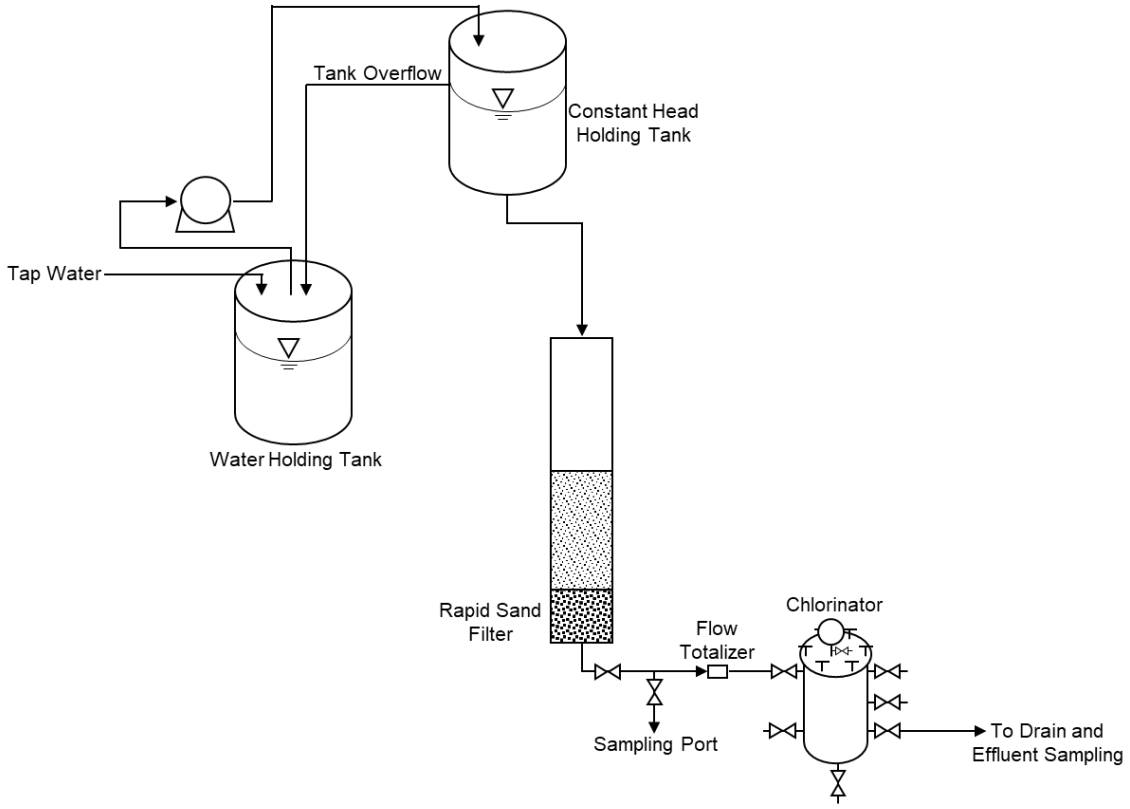

Figure 37. Flow diagram for the lab set up.

3.2.4. Data Collection Equipment

The same equipment that is used in the water lab in Cange will be used for these experiments. The HACH DR900 Multiparameter Portable Colorimeter will be used to

measure the free chlorine of samples using DPD Method 10069 which measures free chlorine at high ranges (0.1 to 10.0 mg/L Cl_2). This method works by the addition of a DPD (N,N-diethyl-p-phenylenediamine) indicator powder pillow to a 5-mL sample of the chlorinated water. Hypochlorous acid or hypochlorite ion reacts immediately with the indicator to form a pink color. The colorimeter can then measure the intensity of the color which is proportional to the chlorine concentration using a 520 nm wavelength (HACH, 2014). Digital colorimeters are the most accurate way to measure free chlorine in the field or in developing settings and offers highly accurate readings, fast results, and is EPA approved (Centers for Disease Control and Prevention (CDC), 2014).

3.2.5. Experiment 1: Determination of Tablet Dissolution Time

In order to gain a better sense of how long it takes for a tablet to completely dissolve, one chlorine tablet was placed in a five-gallon bucket of tap water. The basket from the experimental chlorinator will be used to hold the tablet so that it can easily be pulled from the bucket and weighed. The tablet was weighed every 30 minutes to determine how quickly mass is leaving the tablet. The pH of the solution in the bucket will also be monitored as a way to observe the chlorine concentration increasing as the tablet dissolves. It was too difficult to measure the actual free chlorine concentration as the concentration in the bucket was very high, but the pH was a good indicator of this as pH increases with a higher concentration of hypochlorite ions present in the water.

This experiment also gave an indication of how increasing the pH of the water surrounding the tablet affects its dissolution rate. For the rest of the experiments for Objective 2 tap water with a small amount of residual chlorine concentration was used. If the free chlorine concentration surrounding the tablet had a large effect on the dissolution rate of the tablet itself, it would need to be accounted for that the water entering the chlorinator already had a small level of chlorine present. It was expected, however, that the residual chlorine level present in tap water would not affect the experiments as the concentration of the tablets was much higher.

3.2.6. Experiment 2: Effect of Flow Rate Through the Chlorinator

To determine the effect that flow rate has on the tablet dissolution, a set of five different experiments was conducted at differing flow rates ranging from 0.44 gpm to 2.25 gpm. The inlet and outlet locations for these experiments were the same as the chlorinator used in the Cange water system with the inlet at the top of one side of the chlorinator and the outlet directly below it towards the bottom of the chlorinator. As described later, this will be known as the bottom left outlet location. Only one tablet was placed in the basket. Tests were run for a total of seven hours and the free chlorine concentration were tested at the outlet every 30 minutes. After each experiment, the tablet was allowed to dry and was weighed to determine the amount of mass lost from the tablet.

3.2.7. Experiment 3: Effect of Number of Tablets in Chlorinator

Similar to Experiment 2, to determine the effect the number of tablets has on the resulting outflow concentration, three experiments were conducted using one, two, and three tablets. The flow rate was held constant for all three tests around 1.16 gpm and the outlet was at the lower left outlet location. Each test was run for a total of seven hours and the free chlorine concentration was tested at the outlet every 30 minutes. After each experiment, the tablet was allowed to dry and was weighed to determine the amount of mass lost from the tablet.

3.2.8. Experiment 4: Effect of Different Outlet Locations

The last lab experiment was designed to determine the effect that different outlet locations had on the resulting chlorine concentration leaving the chlorinator. The different geometries used can be seen in Figure 38 and will be referenced by their outlet location. While the chlorinator is a cylinder and therefore does not have a right and left side, for the simplicity of describing location, a 2D view with the inlet on the top left of the chlorinator will be used. The four outlet locations tested were bottom left, bottom right, middle right, and top right. The bottom left outlet location is the current design of the chlorinator used in the Cange water system.

For this experiment one chlorine tablet was used and the flow rate was held constant around 1.16 gpm. Each experiment was run for a total of seven hours and the free chlorine concentration was tested at the outlet every 30 minutes. After each experiment,

the tablet was allowed to dry and was weighed to determine the amount of mass lost from the tablet.

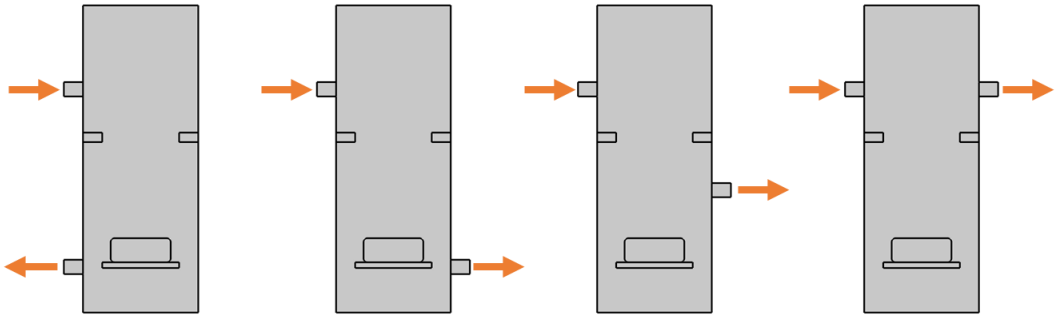

Figure 38. Four different outlet locations tested. From left to right these outlet locations will be referenced as: bottom left, bottom right, middle right, and top right.

3.3. Objective 3: CFD Model Validation and Calibration

The final objective was to review and incorporate the lab data into the CFD model of the chlorinator to further refine the model as an accurate depiction of reality. These updated models also assisted in understanding the results from the experimental data. Some of the assumptions or simplifications from the COMSOL models in Objective 1 were addressed and changed to improve overall model performance.

3.3.1. Study 1: Comparison of COMSOL and Lab Results

First, the models were changed to have turbulent flow physics. This was done because the laminar models from Objective 1 did not allow for the models to converge using the flow rates used in the lab experiments. This was also one simplification from the

earlier models that was thought to have one of the largest potentials for affecting the results; the Reynold's numbers calculated in Appendix B seem to support that the flow is turbulent especially at the flow rates used in the system in Haiti. The κ-ε turbulence model which is built into the COMSOL program was used as it is known to be one of the one of the most useful turbulence models suitable for numerical modeling (Clark, 2009). This physics interface in COMSOL uses the Navier-Stokes equation (Equation 4) for conservation of momentum and the continuity equation (Equation 3) for conservation of mass. Turbulence effects are modeled using the two equations for κ and ε. The equation for κ calculates turbulent kinetic energy and is as follows:

$$\kappa = \frac{1}{2}\overline{u_i' u_i'} = \frac{1}{2}\overline{u_1'^2 u_2'^2 u_3'^2} \tag{6}$$

The equation for ε calculates the turbulent energy dissipation and is as follows:

$$\varepsilon = \frac{v}{2}\overline{\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)} \tag{7}$$

The transport of diluted species physics was again used for the mass leaving the chlorine tablet and moving through the chlorinator. These physics were coupled together so that the effects of fluid flow and species transport were tied together in the model. The boundary conditions for each condition were kept the same from the models in Objective 1, simply switching the laminar flow and turbulent flow physics.

The next big difference in these updated models was the switch to using stationary studies instead of time dependent models. This change came after observing the lab results that will be discussed in detail in the Results and Discussion section of this thesis. Largely,

it was seen that the free chlorine concentration leaving the chlorinator over time was actually very consistent in the lab experiments which was not expected to be the case. The chlorinator itself could also be viewed as a quasi-steady state condition because, compared to the time scale for which the hydrodynamics adapt to changes in tablet size (on the order of seconds), the change in tablet size is very slow (on the order of tens of minutes to hours). Making this change also meant not using the moving mesh set up to represent the chlorine dissolution.

Most other model elements were kept the same as the original model, but the geometry was updated to better match the dimensions of the chlorinator used in the lab. A maximum element size of 1.07 in and minimum element size of 0.005 in were used to create the mesh for these analyses. This resulted in a mesh with around 12,000 domain elements and 600 boundary elements depending on the number of tablets modeled in the chlorinator. An additional change that was made was the inclusion of several new parameters represented by variables to allow certain things about the models to be changed easily. These parameters included flow rate, the diffusion coefficient of the tablets, the concentration at the surface of the tablet, and the mass flux of chlorine from the chlorine. If these parameters are not specified as being changed for these models.

During these analyses, two different conditions were investigated for modeling the boundary between the chlorine tablet and the water in the chlorinator. The first was by representing the boundary as a constant concentration. This was the method used to represent the boundary in the models created in Objective 1. It was difficult to determine an acceptable value for this concentration without the experimental data. In order to

determine an appropriate value, a parameter sweep was completed with surface concentration values from 0 mg/L to the solubility limit of calcium hypochlorite which is 210,000 mg/L.

The other condition investigated was using a constant flux boundary at the tablet's surface. After seeing that the mass rate of chlorine leaving the tablet was constant for the outlet location used in the Cange water system in the results from Objective 2, it was thought that this boundary condition would be appropriate for representing the tablet behavior. Flux values were swept from 0.2 to 0.6 $mol/m^2 \cdot s$ which corresponds to a mass dissolution rate of 1095 mg/min to 3284 mg/min found by multiplying by the tablet's surface area exposed to flow.

By sweeping the values for each condition, an appropriate value based on the experimental results was determined. Models were then run at varying flow rates, using different numbers of tablets, and for the different outlet locations to compare the models to the experimental results.

3.3.2. Study 2: Effect of Varying Diffusion Coefficient

A study was conducted to determine the effect that diffusion coefficient of chlorine had on the resulting concentration leaving the chlorinator. There was not a clear diffusion coefficient identified in the literature for calcium hypochlorite, but we would expect it to maybe be a little slower than sodium chloride (1.35×10^{-5} cm^2/s) because it is a larger molecule and potentially similar to something like hydrogen sulfide (1.41×10^{-5} cm^2/s)

(Clark, 2009). To see how large an effect changing the diffusion coefficient would have on the resulting concentration, a parameter sweep was performed for various diffusion coefficients in this range and the resulting concentrations were tabulated. Eleven values were used between 1×10^{-10} and 1×10^{-8} m^2/s.

3.3.3. Study 3: Analysis of Flow Paths

Some of the conclusions drawn for one geometry from the lab results seemed to not hold true when looking at other outlet locations. To help explain this, flow paths were plotted for different chlorinator arrangements including the different outlet locations and with the basket inside the chlorinator. Initially the basket was not included in the models because it made the models much more complicated with a finer mesh needed. Because of the simplifications of making these new models stationary studies and not including the moving mesh, the addition of the basket did not make the model overwhelmingly complicated and the effects of the basket on hydrodynamics were explored.

4. RESULTS AND DISCUSSION

4.1. Objective 1: Initial CFD Modeling

4.1.1. Study 1: Comparison of 2D and 3D Model

A line average for the 2D model and a surface average for the 3D model were taken at the outlets of the two models and Figures 39 and 40 show plots of the average concentration leaving the chlorinator vs. time. Figure 39 shows the 2D model where the concentration increased quickly at first, started to even out, and then increased slightly again. This is likely due to the effect of some of the mass moving around the bottom of the basket to reach the outlet instead of moving smoothly around the tablet such as in the 3D model which shows much smoother results.

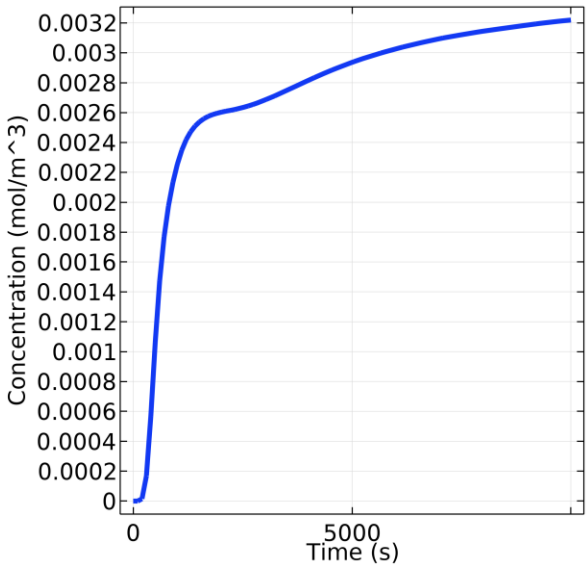

Figure 39. Average chlorine concentration leaving the chlorinator as a function of time for the 2D Model.

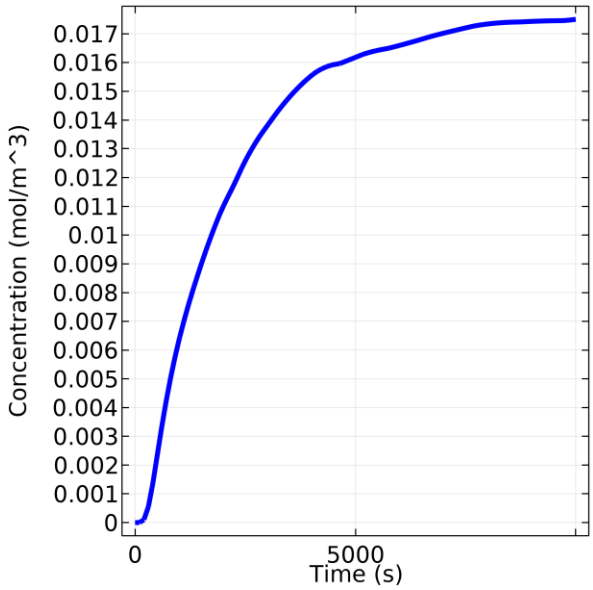

Figure 40. Average chlorine concentration leaving the chlorinator as a function of time for the 3D Model.

Overall, the results for these simulations show very similar behavior for the two configurations and so the remainder of the models were run as 2D. It should be noted that this study also showed that while the 2D model is an appropriate approach to modeling concentration behavior, the predicted outflow concentration value was much different than the 3D prediction. When running other 2D models it needs to be kept in mind that the results are not completely accurate due to this simplification.

4.1.2. Study 2: Effect of Various Numbers of Tablets

The second study determined the effects of the number of tablets in the chlorinator. The final timestep in the study shown with the velocity profile for each model can be seen in Figure 41.

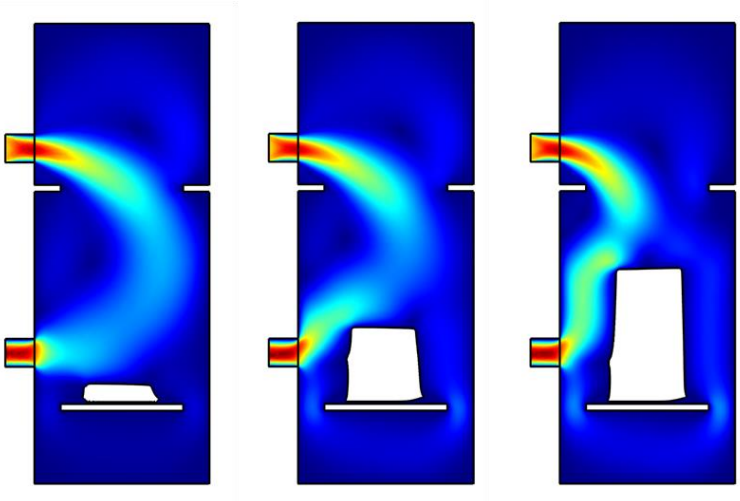

Figure 41. Final timestep for one, three, and five tablets dissolving plotted with the respective velocity flow profile.

Similar to in the first study, the average concentration leaving the chlorinator for each of the models with different numbers of tablets were plotted in Figure 42. From this image, the three models appear similar in nature with a large peak of chlorine in the beginning of the study with a decline following with differences in the peak amount of chlorine leaving the system.

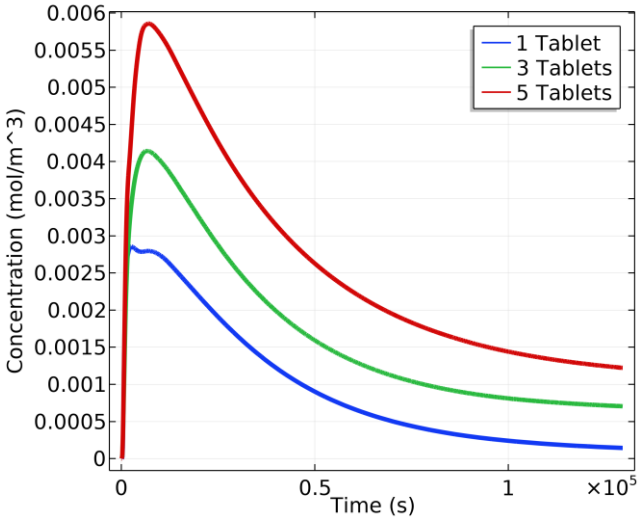

Figure 42. Average concentration leaving the chlorinator for differing numbers of tablets.

To compare the behavior of the different numbers of tablets, the absolute value of the derivative of the plots in Figure 42 was taken a plotted in Figure 43. The idea behind this is that the closer the mass rate of chlorine leaving the system is to being constant, the more constant the slope of concentration over time will be. This means on the derivative plot, the lower the value, the closer the model is to running at a constant mass flux of chlorine leaving the system.

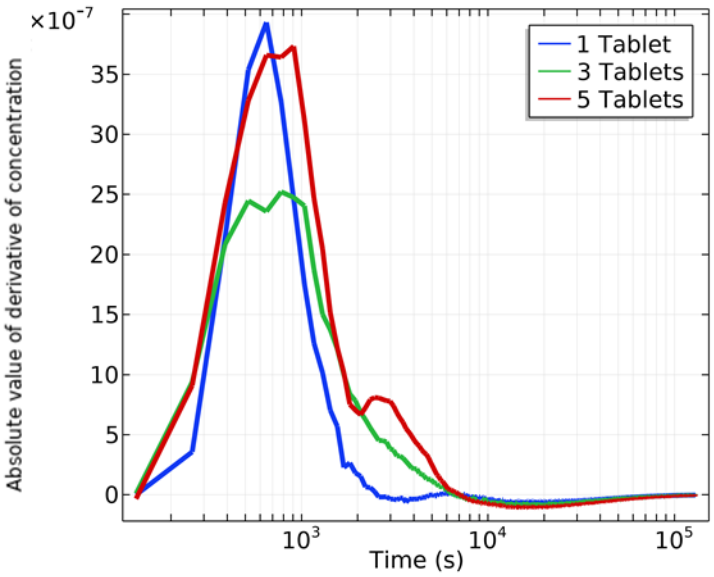

Figure 43. Absolute value of the derivative of the average concentration leaving the chlorinator for one, three, and five tablets.

Figure 43 shows that there was not much of a difference in the slopes of the graphs indicating the concentration of chlorine leaving the system. It does, however, show that the current design for the chlorinator creates a large peak in the amount of chlorine leaving the system which leads to varying chlorine concentrations within the water distribution

network. This has been supported by the data collected in Haiti and is what led to the third study seeing if design improvements could be made.

4.1.3. Study 3: Effect of Changing Inlet and Outlet Location

Figure 44 shows all of the geometries tested at the final timestep plotted with their respective velocity profiles. From these images, a lot can be seen about how the tablets are dissolving by their shape and size after the duration of the modeling. For example, the last two designs tested where the flow entered from either the top or bottom showed the most consistent overall tablet dissolution when looking at shape.

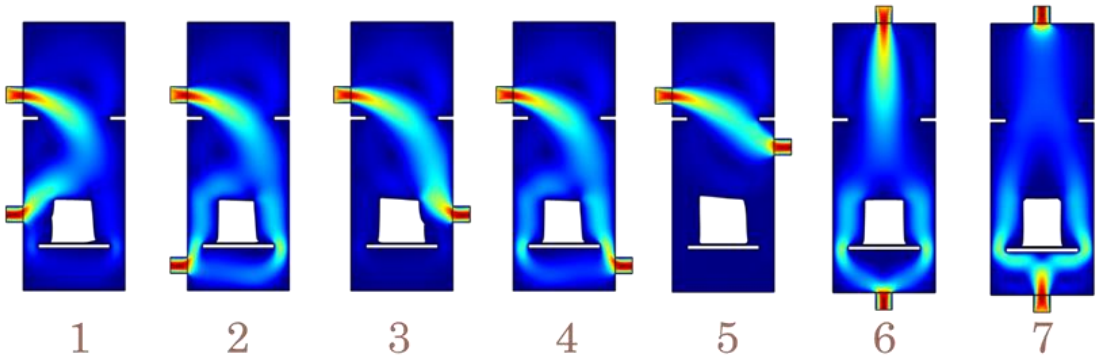

Figure 44. Geometries tested at their final timestep plotted with their respective velocity distribution.

Figure 45 shows the average concentration leaving the chlorinator for the models in Figure 44 and similar to what was shown in the second study, the absolute value of the derivative of these results is plotted in Figure 46.

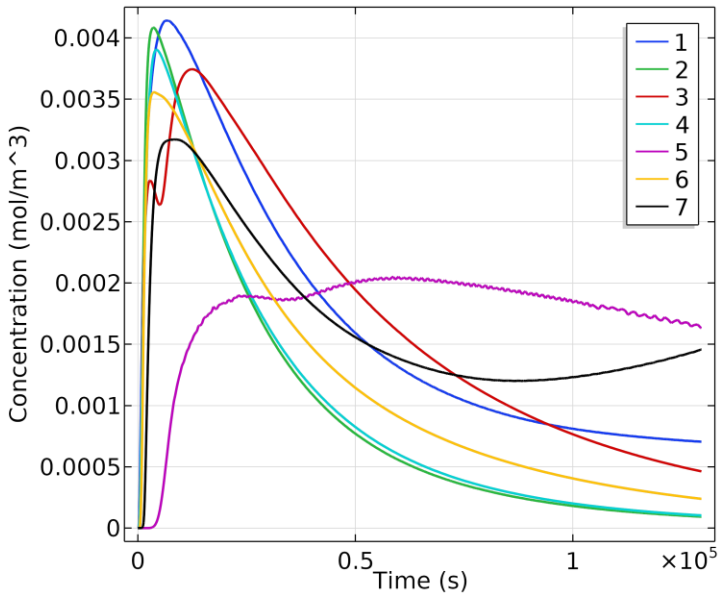

Figure 45. Average concentration leaving the chlorinator over time for the original and 6 additional chlorinator designs.

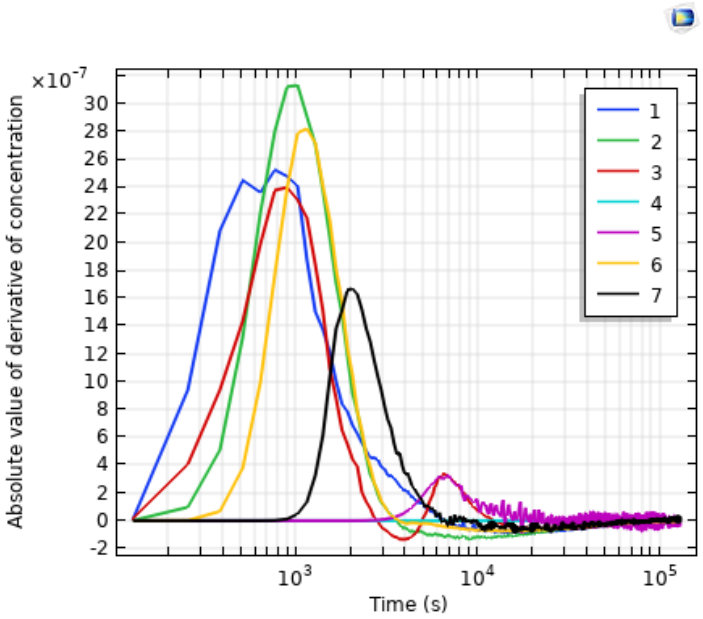

Figure 46. Absolute value of the derivative of the average concentration leaving the chlorinator over time for the original and 6 additional chlorinator designs.

From the results shown in Figures 45 and 46, geometry 5 (labeled in Figure 44) was the only design that appeared to show a significant variation from the concentration pattern of the current design (modeled as geometry 1). A couple of the other designs showed slight improvements, but geometry 5 was the only one that showed a profile relatively close to a constant stream of chlorine.

After seeing these results, an additional model was run where the outlet was placed on the opposite side of the chlorinator from the inlet and was moved to various heights ranging from 4 in to 12 in from the bottom of the chlorinator. As a comparison, the inlet height is at 11 in. The results of these simulations can be seen in Figure 47.

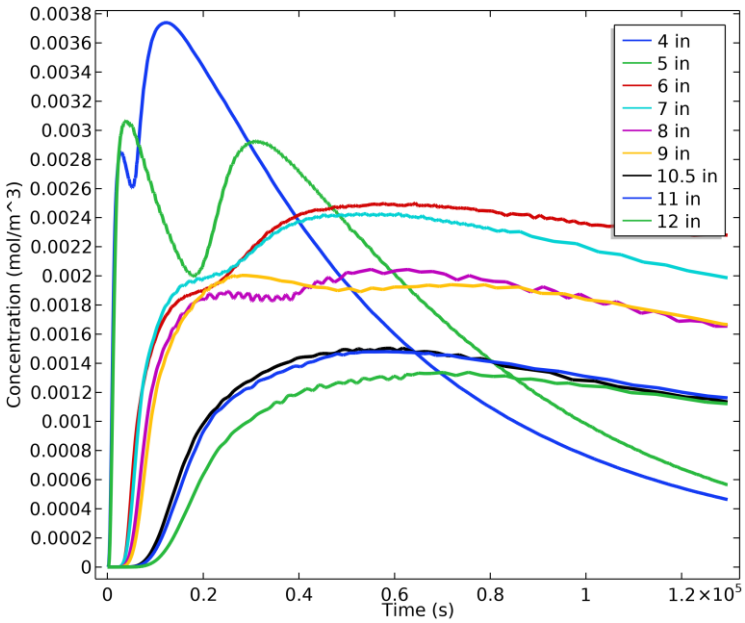

Figure 47. Average concentration leaving the chlorinator over time when the outlet is place at various heights on the opposite side of the chlorinator from the inlet.

As the outlet was moved up the side of the chlorinator, the resulting concentration rate leaving the system had less variation in their slope. After the outlet height was equal to or above 6 inches, all the plots have a relatively constant level of chlorine in the effluent unlike the other geometries. This is likely because at these heights, the majority of the flow moving through the chlorinator does not interact directly with the tablet. For the models where the main flow path interacts with the tablet, the tablet experiences a higher velocity at its surface. This causes the tablet to erode at a faster rate and causes the overall concentration of the effluent to decrease as the tablet becomes smaller.

The models where the inlet and outlet are located at positions that result in the main flow path not interacting with the tablet directly have a much smaller velocity at the tablet's surface. This allows for the tablet to dissolve at a more consistent rate and diffuse throughout the chlorinator body. The flow stream through the chlorinator then picks up some of this diffused mass as it comes through the chlorinator. It is likely that these models are acting in a fashion similar to more traditional erosion chlorinators where dry tablets are stacked above an area where flow is directed to just hit the bottom tablet. Here, instead of having a stack of tablets, there is an area of increased concentration within the chlorinator that stays pretty consistent as the tablet dissolves and diffuses through the chlorinator. The flow then wisps away chlorine from this highly concentrated zone and more diffuses into its place.

While many simplifications were included in the initial computational models, their behavior was enough to support the idea that outlet location was important in chlorinator design and operation, so there could be an optimal outlet location to better

control the mass rate leaving the chlorinator over time. The modeling data were used to plan laboratory experiments where real chlorine measurements could be taken.

4.2. Objective 2: Experimental Data Collection to Determine Chlorine Tablet Behavior

4.2.1. Experiment 1: Determination of Tablet Dissolution Time

The purpose of this experiment was to gain a better sense of how long it takes for a tablet to completely dissolve. The results of placing one chlorine tablet in a five-gallon bucket of tap water can be seen in Figure 48.

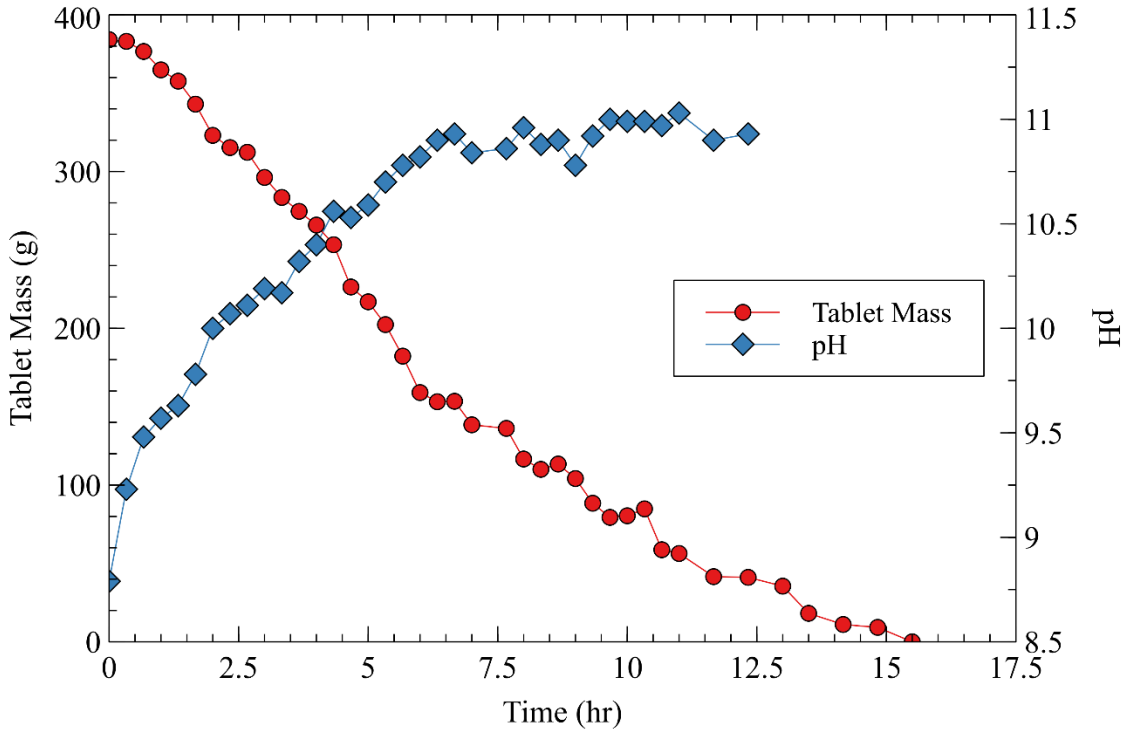

Figure 48. Tablet mass and pH as a single tablet dissolved in five gallons of water.

The results of this experiment show that the tablet dissolved at a relatively constant rate over time, slowing down only slightly towards the end of the experiment. As predicted, the pH of the solution rose during the experiment as the concentration of free chlorine rose. The tablet took around 15.5 hours to completely dissolve at an average rate of 413 mg/min.

These results increase confidence for moving forward with further experiments that will use tap water as the influent water which contains a small amount of residual chlorine. Seeing how little the high concentration of chlorine in the bucket affected the tablet dissolution over time gives confidence that the small amount of residual chlorine in the tap water will not impact the behavior of the following experiments.

4.2.2. Experiment 2: Effect of Flow Rate Through the Chlorinator

For this experiment, the original geometry of the chlorinator and one tablet were used to test five different flow rates: 0.44, 0.83, 1.16, 1.83, and 2.25 gpm. The results showing the free chlorine concentration leaving the chlorinator over time can be seen in Figure 49.

These results showed that at higher flow rates, lower concentrations of chlorine were observed in the effluent. What was interesting about these results was that there was not a large peak in chlorine concentration followed by a steady decline as was expected for this geometry based on the initial COMSOL models. Overall, all five flow rates showed a relatively constant concentration in the effluent following an initial peak at the beginning of the experiment. This peak was most likely caused by the fact that the tablet was placed

in the chlorinator and began diffusing as the chlorinator was sealed, filled with water, and pressurized. After this process, flow began, and the system likely experienced a slug of chlorine that needed to be flushed from the chlorinator body. This process appears to take around 30 minutes to an hour based on the concentrations tested before seeming to level off. This reasoning is also supported by the fact that the peaks were higher for lower flow rates. At lower flow rates it would take a longer amount of time to wash out the initial slug and allow a greater amount of chlorine to diffuse before reaching a steadier state of operation.

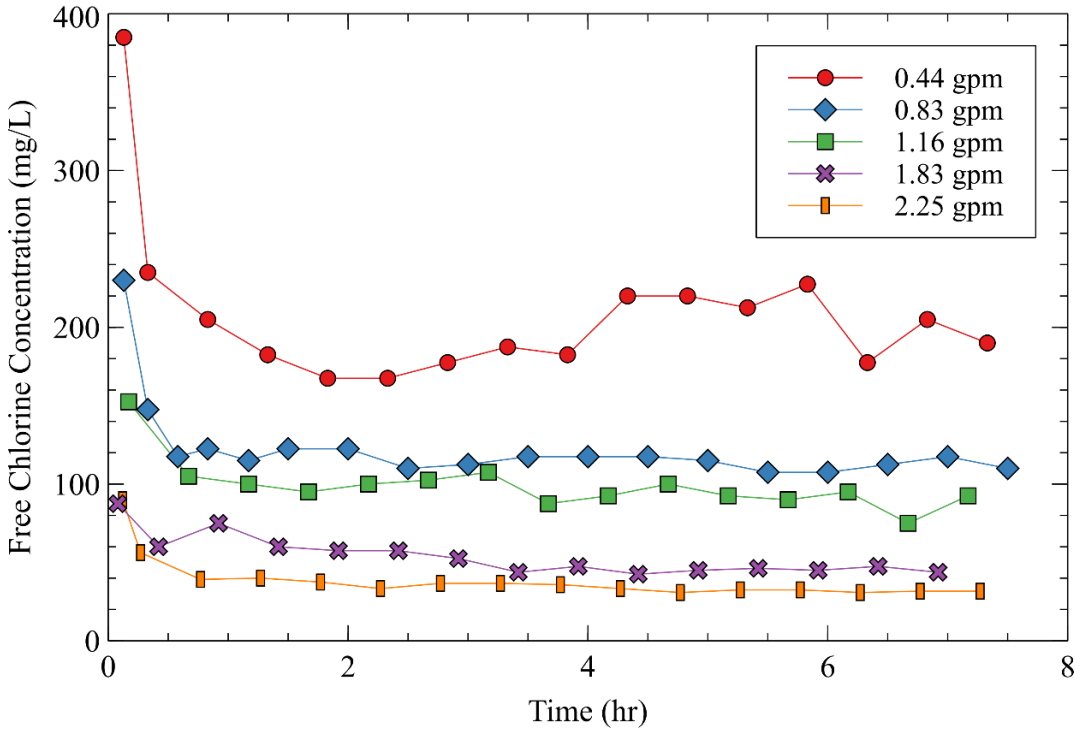

Figure 49. Experimental results of free chlorine concentration in the effluent of the chlorinator at different flow rates using the original geometry and one chlorine tablet.

Seeing these results challenged the initial thought that the original chlorinator geometry with the inlet at the top and outlet on the bottom of the same side of the body would result in a decreasing amount of chlorine leaving the chlorinator. Of course, it would be expected that the concentration would eventually have to decrease as the tablet approaches complete dissolution, but over the seven hours of the experiments, the chlorine concentration was fairly constant.

To better understand the effects of flow rate on the outlet concentration, the average free chlorine concentration was calculated following the first hour of testing to avoid including the initial slug of chlorine in the analysis. This average concentration was plotted against each flow rate in Figure 50. Additionally, on this plot, the expected concentration based on completing a mass balance of the tablet was calculated by taking the mass of the tablet before and after the experiment after allowing time for the tablet to dry. The difference in mass was then divided by the flow rate multiplied by the time each experiment was allowed to run. This results in the total loss of mass from the tablet over the total volume of water that had passed through the chlorinator during the experiment. This was converted to mg/L and plotted in Figure 50.

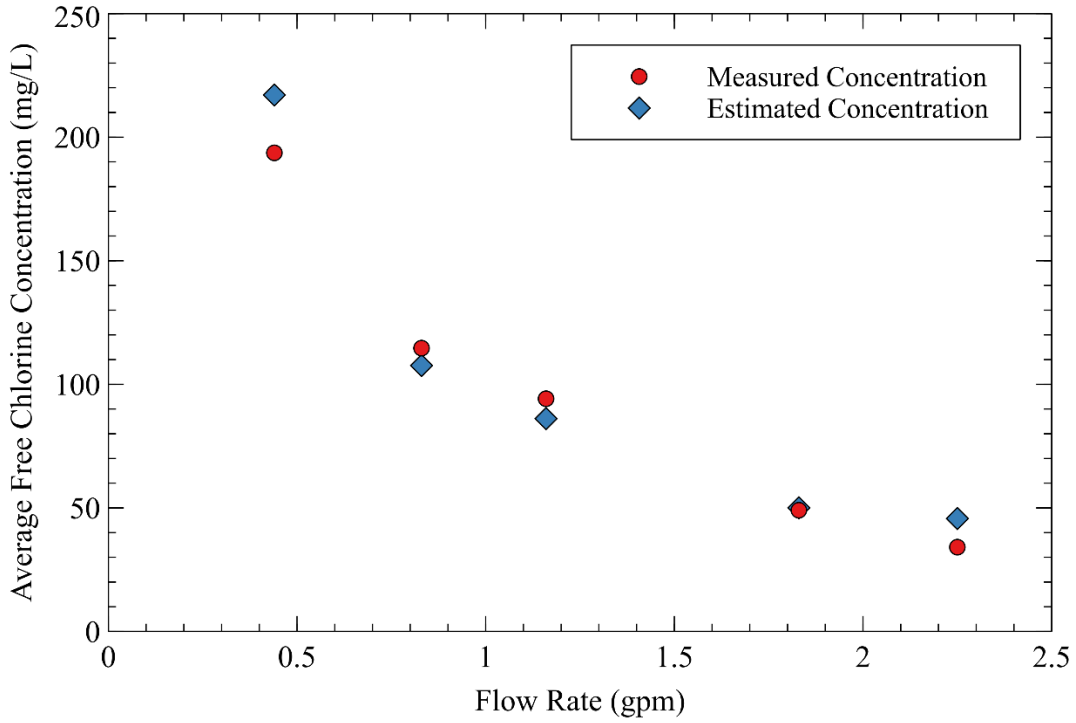

Figure 50. Average free chlorine concentration as tested in the effluent of the chlorinator at different flow rates using the original geometry and one chlorine tablet as well as calculated free chlorine concentration estimated using change in tablet mass.

It was not expected that the estimated concentration value be the same as the average tested concentration from the experiments as the entire mass of the tablet was used. The tablet was only comprised 65 to 76% calcium hypochlorite which would make the estimated concentration calculated using the tablet mass too large. The average concentration from the measured values in the experiments did not take into account the slug of chlorine at the beginning of each experiment, but the estimated concentration using the mass of the tablet did include the mass lost during that period. This means that it would be expected that the concentration estimated using the mass of the tablet would be higher than the average concentration calculated ignoring the slug of chlorine in the first hour of

the experiments. It is difficult to calculate exactly what the expected average free chlorine concentration for each flow rate should be based solely on the difference in tablet mass because of the previously stated reasons. The closeness of the values to the measured lab values could have been coincidental, but the fact that the data show the same trends gives confidence in the results.

The results of this experiment to determine the effects of flow rate on the dissolution of the tablet show that as the flow rate increases a decreased free chlorine concentration can be expected in the effluent; however, this relationship is not linear. To better understand this relationship, the mass dissolution rate was calculated for each flow rate's average concentration by multiplying the flow rate and the average concentration then converting the units as seen in Table 1. Next, the predicted chlorine concentration was calculated using the mass dissolution rate calculated for the first flow rate (0.44 gpm) which was equal to 322 mg/min. This was done by diving the mass dissolution rate by the flow rate and converting units to mg/L. This was done to gain an understanding of what we would expect the relationship between flow rate and concentration to be if the mass dissolution rate of the tablet were constant. The calculations showed that the relationship expected can be represented using a power function which was plotted in Figure 51. The function plotted in Figure 51 is $C = 85.2 \times (1/Q)$.

Table 1. Calculated mass dissolution rates for each flow rate experiment as well as the predicted chlorine concentration using the mass dissolution for a flow rate of 0.44 gal/min.

Flow Rate (gal/min)	Measured Chlorine Concentration (mg/L)	Mass Dissolution Rate (mg/min)	Predicted Chlorine Concentration (mg/L)
0.44	193.65	322.08	193.65
0.83	114.64	359.67	102.66
1.16	94.17	412.92	73.45
1.83	49.06	339.37	46.56
2.25	34.10	290.02	37.87

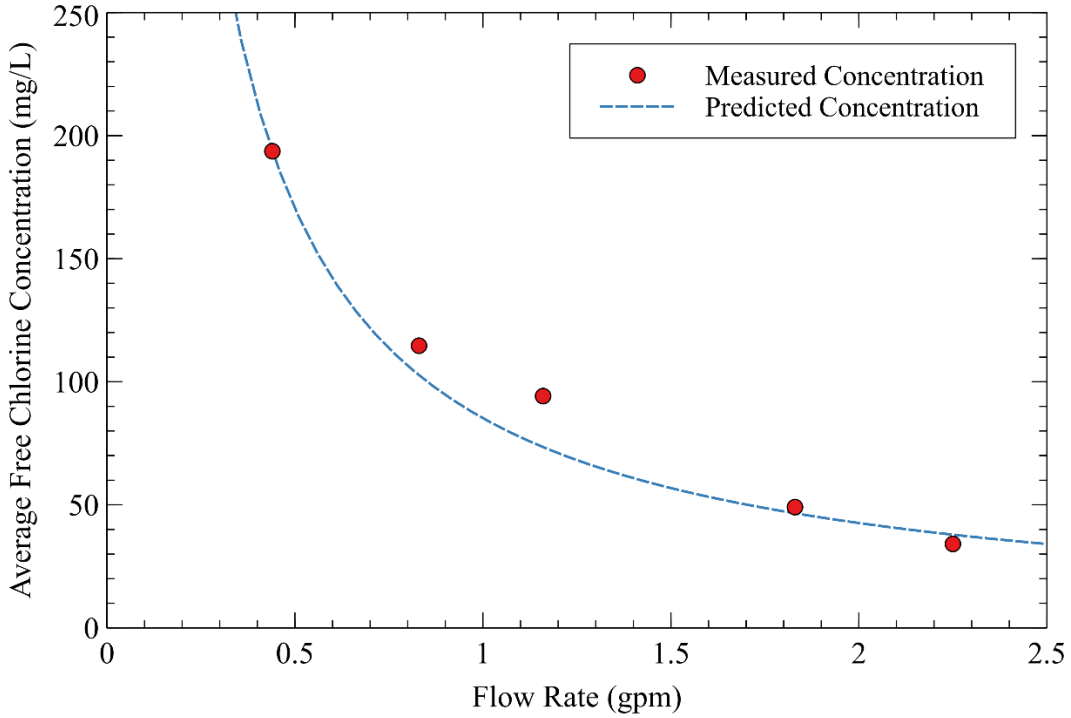

Figure 51. Comparison of the average free chlorine concentration tested in the lab for different flow rate values and the predicted concentration for a constant mass dissolution rate.

As seen in Figure 51, the measured concentrations from the lab correspond to the predicted behavior if the mass dissolution rate was constant at any flow rate. If higher flow was causing the tablets to erode more quickly, we would expect all of the points to fall

above the line as increased erosion would cause higher concentrations, however this is not the case. It is hard to imagine that the water flowing around the tablet does not play a large part in its dissolution. In fact, a name for chlorinators similar to this one is an erosion chlorinator alluding to the fact that water "erodes" away chlorine from the tablet. While this could still be happening to some extent within the chlorinator, overall, the process appears to be limited by the dissolution rate of the tablet. This was also supported by the fact that throughout all of the experiments the tablets held their original shape. An example of a tablet before and after testing can be seen in Figure 52. If the reaction between the water and tablet were playing a large role in the tablet's dissolution, it would be expected to see the tablet dissolve faster in areas where the flow rate is higher.

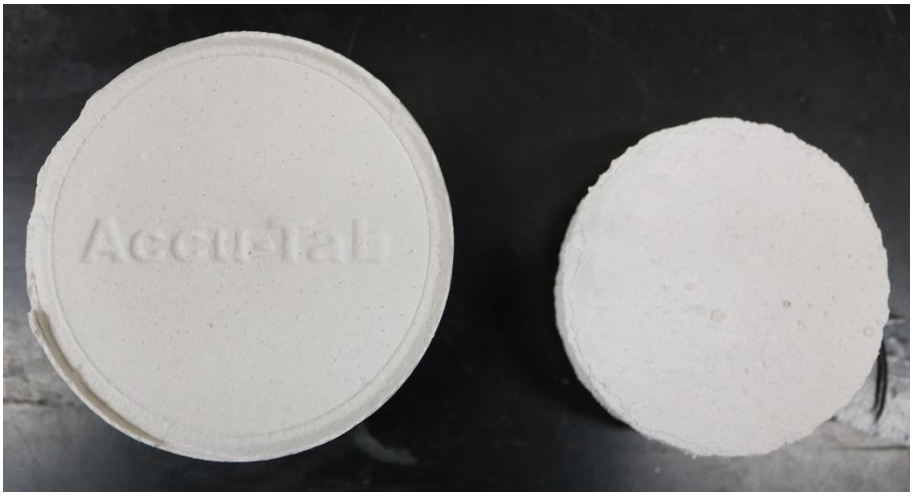

Figure 52. Chlorine tablet before and after one of the dissolution tests occurring over 7 hours.

Overall, the results of this experiment seem to suggest that the mass dissolution rate of the tablet for the chlorinator in this geometric configuration is constant despite changes

in flow rate. The average chlorine mass dissolution rate for each of these experiments was 345 mg/min with a standard deviation of 46 mg/min and a 0.13 coefficient of variation.

Another benefit if the tablet does dissolve at a constant rate is that it makes operation in the field simpler. Because the chlorinator operates on a small side stream of the full system flow and is mixed back in following chlorination, one parameter that was desirable to observe is how the flow rate through the chlorinator effects the overall concentration of the total system flow. In order to calculate this, a mass balance was performed where the side stream from the chlorinator comes back into contact with the main system line. Using the calculated chlorinated concentration leaving the chlorinator assuming a constant mass dissolution rate and an average flow rate for the system, the overall expected system concentration at the point of mixing was calculated. The results of this calculation can be seen in Table 2 for a system flow rate of 40, 50, and 60 gpm. The results of this analysis showed that regardless of the flow rate chosen for the side stream chlorination, the overall system concentration would result in the same value as shown in the last column.

Taking this information, the predicted system concentration was calculated for a range of system flow rates and plotted in Figure 53. These predicted values were represented by a very similar power function found for the predicted concentrations leaving the chlorinator with the difference resulting from the difference in dissolution rate used.

Table 2. Predicted system concentration based on different flow rates through the chlorinator side stream and assuming a constant tablet dissolution rate of 345 mg/min.

System Flow Rate (gpm)	Chlorinator Flow Rate (gpm)	Predicted Side Stream Chlorine Concentration (mg/L)	Predicted System Concentration (mg/L)
60	0.44	207.32	1.52
60	0.83	109.90	1.52
60	1.16	78.64	1.52
60	1.83	49.85	1.52
60	2.25	40.54	1.52
50	0.44	207.32	1.82
50	0.83	109.90	1.82
50	1.16	78.64	1.82
50	1.83	49.85	1.82
50	2.25	40.54	1.82
40	0.44	207.32	2.28
40	0.83	109.90	2.28
40	1.16	78.64	2.28
40	1.83	49.85	2.28
40	2.25	40.54	2.28

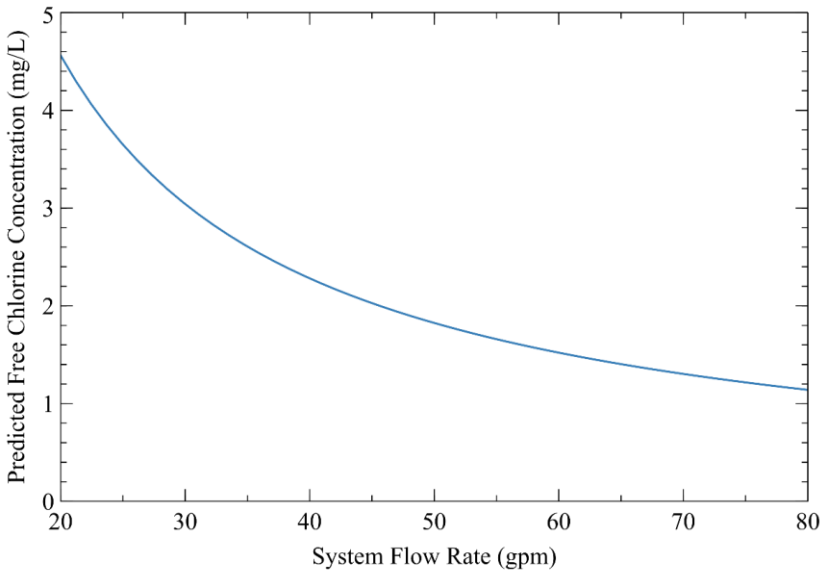

Figure 53. Predicted system concentration at the point of mixing with the side stream chlorinated flow based on the assumption of a constant tablet dissolution rate and one tablet. The flow rate shown in this plot is for the entire system and the concentration shown will be the concentration regardless of the side stream flow rate through the chlorinator.

4.2.3. Experiment 3: Effect of Number of Tablets in Chlorinator

Very similar to the process for Experiment 2, Experiment 3 included running three tests using the original chlorinator geometry, a flow rate of 1.16 gpm, and varying the number of tablets held in the chlorinator basket. The results of these experiments can be seen in Figure 54.

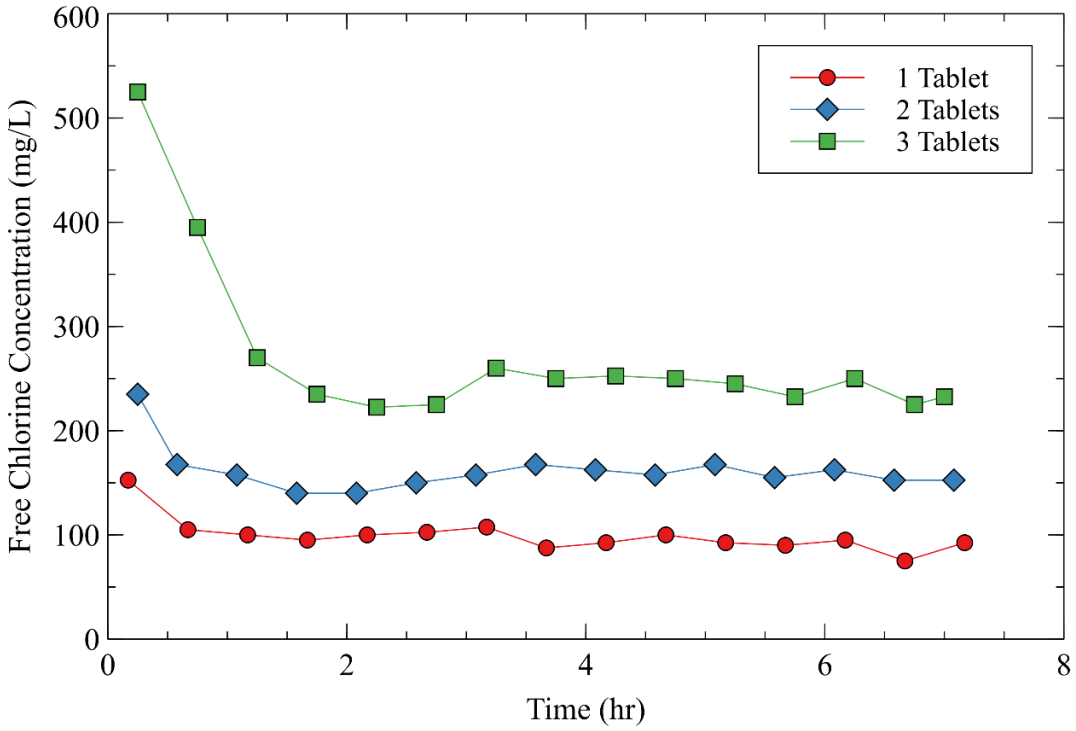

Figure 54. Experimental results of free chlorine concentration in the effluent of the chlorinator for different numbers of chlorine tablets using the original geometry and a flow rate of 1.16 gpm.

As expected, as the number of tablets increased, the concentration leaving the chlorinator increased as well. To better understand how changing the number of tablets affected the outlet concentration, the average free chlorine concentration was calculated

following the first hour of testing to avoid including the initial slug of chlorine in the analysis. This average concentration was plotted against the number of tablets in Figure 55. As with the flow rate analysis, the expected concentration based on completing a mass balance of the tablet was calculated by taking the mass of the tablet before and after the experiment after time was allowed for the tablet to dry. The difference in mass was then divided by the flow rate multiplied by the time each experiment was allowed to run. This results in the total loss of mass from the tablet over the total volume of water that had passed through the chlorinator during the experiment. This was converted to mg/L and plotted in Figure 55. Once again, as with the results from Experiment 2, the values were not expected to match the measured concentrations directly but give a good indication that the trend seen the lab data is trustworthy.

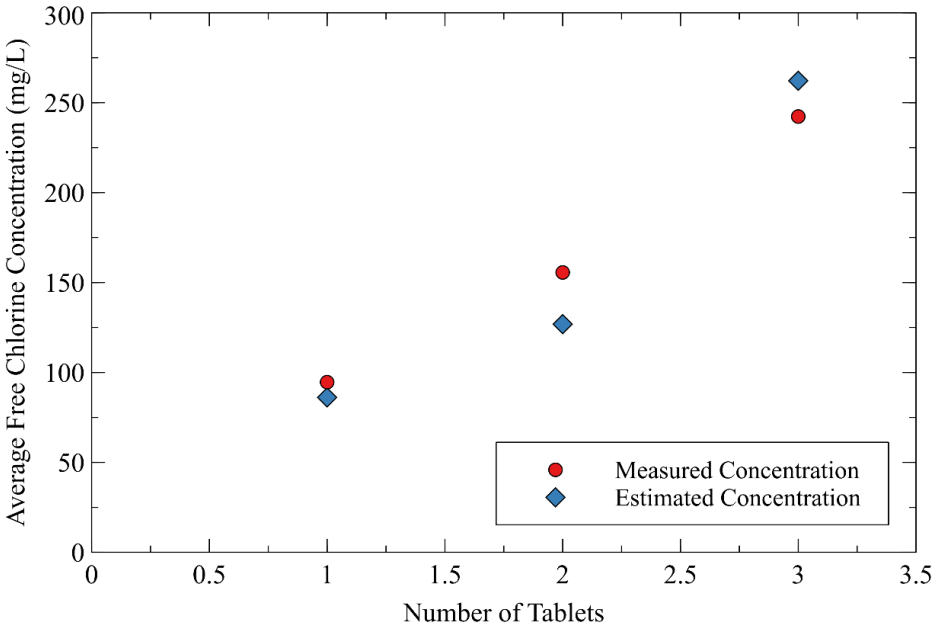

Figure 55. Average free chlorine concentration as tested in the effluent of the chlorinator using different numbers of tablets in the original geometry configuration at a flow rate of 1.16 gpm as well as calculated free chlorine concentration estimated using change in tablet mass.

Figure 55 shows that the increase in concentration based on tablets is not a one to one relationship meaning that using two tablets instead of one does not yield twice the free chlorine concentration. This could likely be explained by the fact that tablets are stacked on top of one another so when two are placed together you lose the surface area of the tablet on the top or bottom. In the COMSOL models, multiple tablets were modeled as one, larger unit. Watching the tablets dissolve in the experimental chlorinator seems to support that this is a valid simplification for modeling as the tablets do stay together while dissolving. Three tablets at the end of testing can be seen in Figure 56.

Figure 56. Three tablets in the chlorinator basket after dissolution testing.

Similar to the analysis for the different flow rate experiments, the mass dissolution rate was calculated for each experiment's average concentration. This time, the mass

dissolution rate was found two different ways. The dissolution rate was still calculated by multiplying the flow rate and the average concentration then converting the units, but also needed to be adjusted to account for the fact that there were more tablets in the chlorinator. The first way this adjustment was made was by dividing the rate by the number of tablets to gain the dissolution rate for just one tablet. The other way was based on the surface area exposed to the water in the chlorinator. When the tablets are stacked on top of one another, only the top surface of the top tablet and the sides of each tablet are exposed to the water. The surface areas for each scenario was calculated and each mass rate was multiplied by the surface area of one tablet divided by the surface area of the number of tablets used in that experiment in order to be adequately adjusted. Additionally, the predicted chlorine concentration was calculated using the mass dissolution rate calculated for the experiment using one tablet which was equal to 414.8 mg/min. This was done by diving the mass dissolution rate by the flow rate and converting units to mg/L. The same adjustments were made for number of tablets using both number and surface area adjustments. The results of these calculations can be seen in Tables 3 and 4.

The calculations in Tables 3 and 4 were done in order to gain an understanding of what we would expect the relationship between number of tablets and concentration to be if the mass dissolution rate of the tablets were constant. The calculations showed that the relationship can be represented using a linear function and the predicted concentrations resulting from both methods of calculation were plotted in Figure 57.

Table 3. Calculated mass dissolution rates for each number of tablets experiment as well as the predicted chlorine concentration using the mass dissolution for one tablet. Adjustments for mass dissolution rate and predicted chlorine concentration were made using the number of tablets used in the experiment.

Number of Tablets	Flow Rate (gal/min)	Average Chlorine Concentration (mg/L)	Mass Dissolution Rate (mg/min)	Predicted Chlorine Concentration (mg/L)
1	1.16	94.6	414.8	94.6
2	1.16	155.6	341.1	189.2
3	1.16	242.3	354.1	283.8

Table 4. Calculated mass dissolution rates for each number of tablets experiment as well as the predicted chlorine concentration using the mass dissolution for one tablet. Adjustments for mass dissolution rate and predicted chlorine concentration were made using the surface area for each number of tablets.

Surface Area of Tablets (in^2)	Flow Rate (gal/min)	Average Chlorine Concentration (mg/L)	Mass Dissolution Rate (mg/min)	Predicted Chlorine Concentration (mg/L)
19.94	1.16	94.6	414.8	94.6
32.21	1.16	155.6	422.4	152.8
44.42	1.16	242.3	476.9	210.7

The function plotted for the adjustment using number of tablets in Figure 57 is $C = 94.6 \times N$ and the function plotted for the adjustment using surface area is $C = 58.1 \times N + 36.6$ where C is the average free chlorine concentration and N is the number of tablets used.

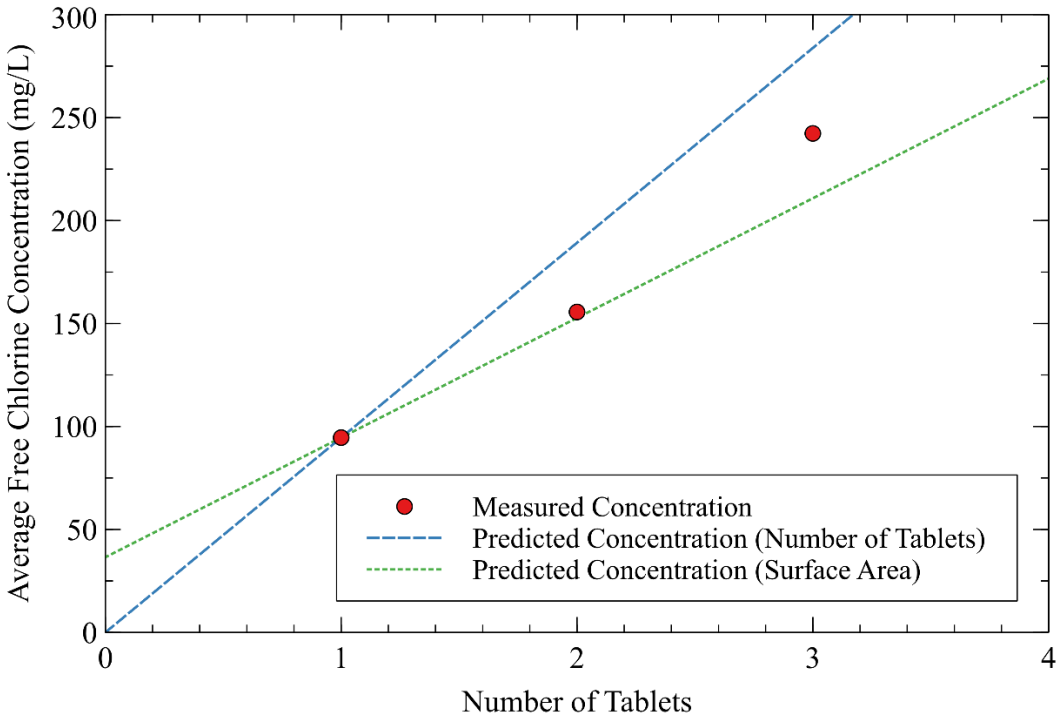

Figure 57. Comparison of the average free chlorine concentration tested in the lab for different numbers of tablets in the chlorinator and the predicted concentration for a constant mass dissolution rate adjusted using the number of tablets and the surface area of the tablets.

As seen in Figure 57, the experimental data fell somewhere in between the two estimates of the predicted concentration. This makes sense as it seems that neither of these methods should be completely correct. There is some surface area at the bottom of the tablets that is exposed through the holes in the basket. There could also be some flow of water and/or dissolution of material from between the tablets that is not accounted for in the surface area estimation. Estimating the concentration using just the number of tablets does not conceptually make sense as a significant amount of the tablet is not exposed to the flow directly when tablets are stacked on top of one another. It is logical, then that the data fell between these two different estimates that both assume a constant mass dissolution

rate once again supporting the thought that the tablets do dissolve at a constant mass rate regardless of the flow around them. The average chlorine mass rate found for a tablet making adjustments using the number of tablets was 370 mg/min with a standard deviation of 39 mg/min and a 0.11 coefficient of variation. The average mass rate found for a tablet making adjustments using the surface area was 438 mg/min with a standard deviation of 34 mg/min and a 0.08 coefficient of variation.

This was a similar mass dissolution rate seen in Experiment 1 where a tablet was dissolved in a bucket of water; however, that mass rate referred to the tablet as a whole and the dissolution rates calculated during these experiments refer to the dissolution of chlorine mass in the tablet. We would expect the tablet dissolution rate to be higher in the chlorinator experiments than in the bucket because of the flow through the chlorinator and the lower chlorine concentration in the water surrounding the tablet. The results showed this to be true as the chlorine dissolution rate calculated refers only to the mass of chlorine leaving the tablet and the tablet mass that has dissolved would be higher as the tablet is comprised of 65-76% calcium hypochlorite.

4.2.4. Experiment 4: Effect of Different Outlet Locations

In order to determine the effects of different outlet locations on the effluent chlorine concentration, the different outlet locations seen in Figure 38 were tested. The results for experiments using different outlet locations, one tablet, and a flow rate of 1.16 gpm can be seen in Figure 58. Four different outlet locations were tested, and the inlet location was

kept the same. The outlet locations are described as if one were looking at a 2-D version of the chlorinator with the inlet at the top left and are all shown in Figure 38 for reference. The highest average concentration occurred when the outlet was at the bottom left, below the inlet at the bottom of the chlorinator. The second highest concentration was when the outlet was placed at the bottom right of the chlorinator. With much lower concentrations present in the effluent, the outlet placed in the middle right side of the chlorinator was next followed lastly by the inlet placed directly across from the inlet at the top right of the chlorinator. While the middle right and top right results are very low, it is important to note that these results were slightly higher than the influent chlorine residual in the tap water so there was some chlorine leaving the system that had come from the tablet.

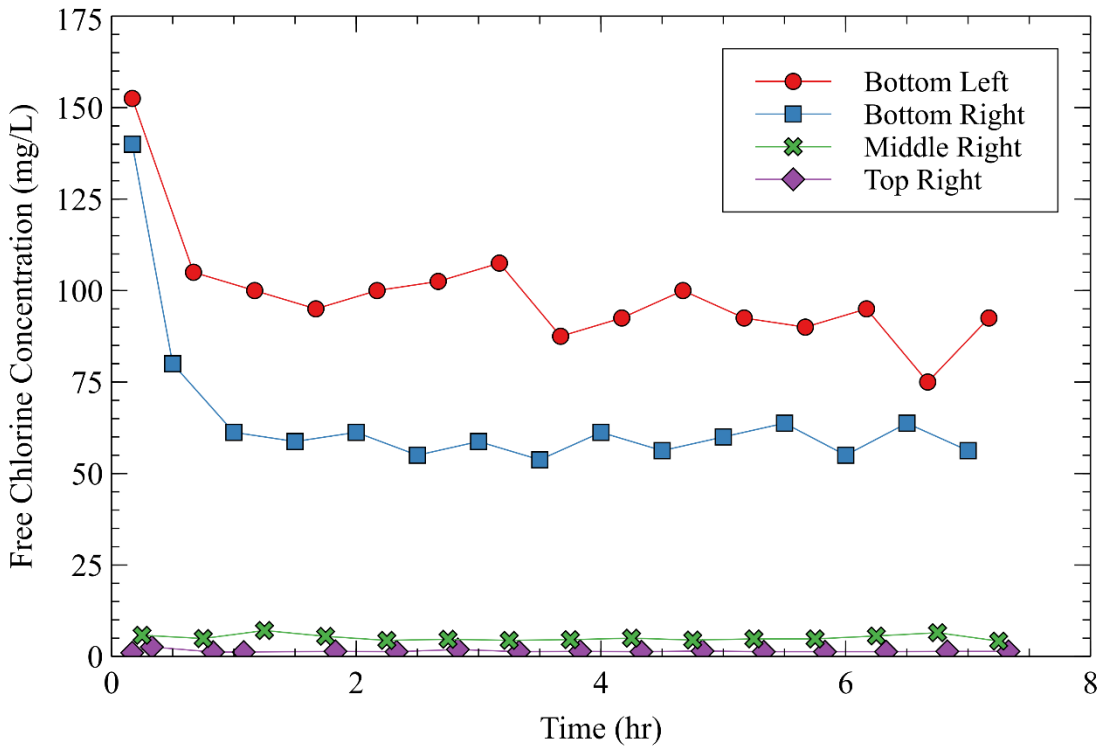

Figure 58. Experimental results of free chlorine concentration in the effluent using four different outlet locations, a flow rate of 1.16 gpm, and one tablet.

These results were slightly unexpected as having the outlet at the top right showed to be the most promising configuration in the initial COMSOL modeling presented in Objective 1. The key issue here is probably the flow rate; the initial COMSOL models used laminar flow physics and a very low flow velocity of 0.001 m/s which compares to a flow rate of 0.008 gpm. In that case the mass transport would be convection limited. Diffusion could transport chlorine faster than the flow, so the whole reactor would be filled with a constant concentration. As flow enters and leaves (slowly) the concentration at the outlet would be high (the same concentration as exists throughout the reactor). The laboratory experiments used a flow rate of 1.16 gpm, resulting in turbulent flow (see Table 6 in Appendix B). In this case the system would be diffusion limited. Water flow came through much faster than chlorine mass could be delivered by diffusion (or even dispersion) to the parts of the reactor feeling the short-circuited flow, resulting in low outlet concentrations.

These results do not necessarily support the hypothesis from the previous two experiments that the tablet mass dissolution rate is the same regardless of the flow in the chlorinator because in this experiment, the flow rate was the same for all of the experiments and much different values in concentration were observed. For these experiments, the dissolution rate is likely different as evidenced by the differences in the change in mass of the tablets over the time the experiments took place. The mass differences recorded for the tablets in this data set showed the same trend as the data with the bottom left having the highest mass difference and the top right having the

lowest. The average concentrations calculated for each experiment using the method described in Section 4.2.2 and 4.2.3 showed that the differences in mass were not as large as expected as shown in Table 5. These results showed that clearly, more mass dissolved from the tablet than was detected in the effluent of the chlorinator. It is likely that while the tablets dissolved in the middle right and top right cases, chlorine was accumulating in the dead areas of the chlorinator while water short-circuited the reactor and left without pulling the dissolved chlorine along. At the same time, because the mass of the tablets at the end of the experiments were not all the same, we see that the tablet's dissolution is not completely independent of flow.

Table 5. Comparison of the average measured chlorine concentration and the concentration estimated using tablet mass lost during the experiment.

Outlet Location	**Average Measured Concentration (mg/L)**	**Estimated Average Concentration Using Tablet Mass (mg/L)**
Bottom Left	94.2	86.1
Bottom Right	58.6	89.1
Middle Right	4.9	79.5
Top Right	1.4	62.0

One theory on why this could be the case is that when the chlorinator is set up using the lower left outlet location, it could be that the maximum dissolution rate possible for the tablet has been reached and so increasing the flow rate around it did not affect the dissolution rate. It is possible that this may not be the case for other geometric configurations. Another thought is tied to flakes of tablet that come off as the tablet dissolves and mostly settle at the bottom of the chlorinator. It has been documented that

these flakes are likely calcium carbonate and calcium chloride (Hodges, 2019). It is possible that these particulates could also contain some portion of the calcium hypochlorite available in the tablet and by settling on the bottom it causes increased importance of flow through this area of the chlorinator.

4.3. Objective 3: CFD Model Validation and Calibration

4.3.1. Study 1: Comparison of COMSOL and Lab Results

The main purpose of this study was to determine if the results from the changes made in the COMSOL model were comparable to the results seen in the lab data from Objective 2. As mentioned in the Materials and Methods section, two different methods were used for representing the boundary between the chlorine tablet and the water. Several parameter sweeps were run to try and understand the effect that changing the boundary condition of the tablet's surface has on the results.

The first condition used was a constant concentration at the boundary. The first analysis of using this boundary involved varying tablet surface concentration using a model that was represented in all the experimental data sets (one tablet, 1.16 gpm flow rate, outlet at bottom left). The concentration was swept for 10 values from 0 to the solubility limit of calcium hypochlorite (21 g per 100 mL or 210,000 mg/L). From the plot seen in Figure 59, it was found that to get the expected effluent concentration of 94.2 mg/L, the surface concentration would need to be set at 11,918 mg/L. This value is much lower than the

solubility limit but considering that flow is sweeping away the concentration and that the tablet is not pure calcium hypochlorite, this seems to be reasonable.

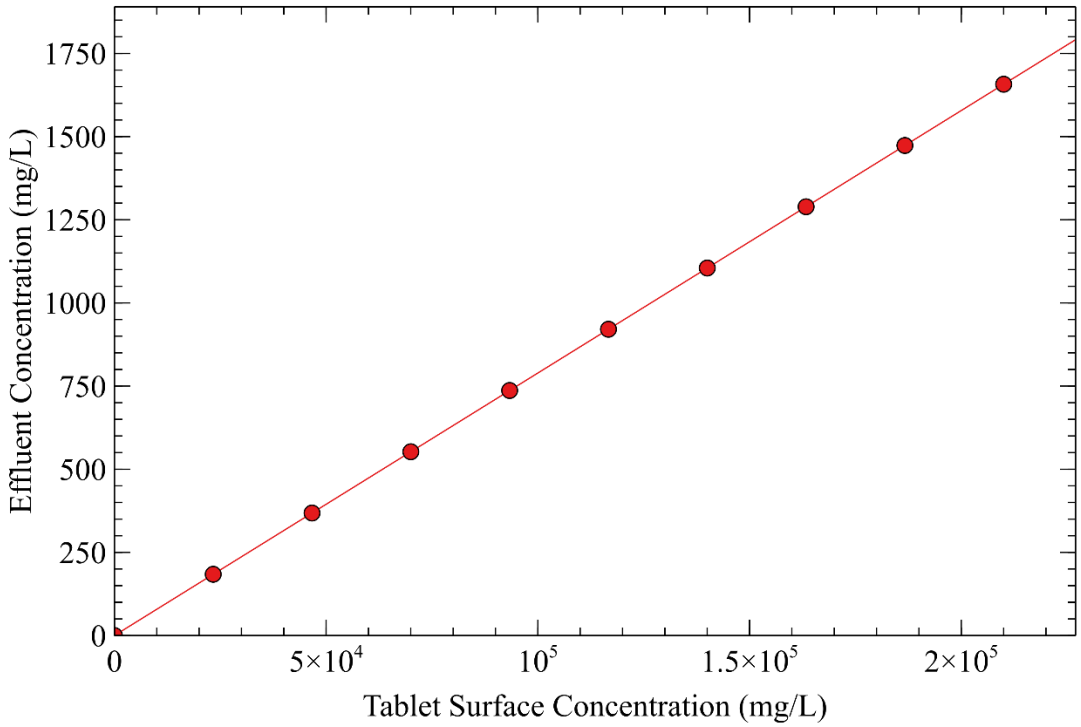

Figure 59. Effluent concentrations calculated by COMSOL using a constant concentration boundary condition for the tablet.

Surface concentration values in this range (10,636 mg/L to 14,181 mg/L) were then swept with the different flow rates used in the experiments in Objective 2. Changing the flow rate did not result in a change in the effluent concentration when using a constant concentration for the tablet surface as shown in Figure 60 where the dashed lines represent the different values used for the tablet surface concentration and the solid blue line is the experimental results.

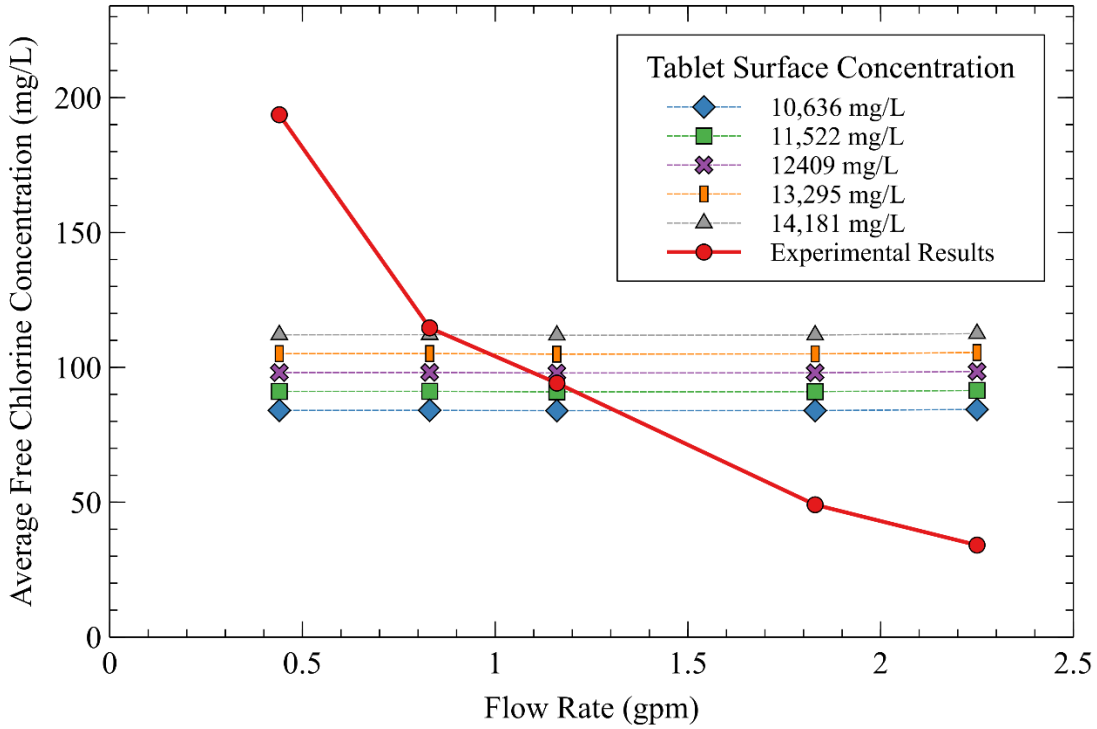

Figure 60. Comparison of concentrations calculated by COMSOL using a constant concentration boundary condition for the tablet in the dashed lines and measured in the lab in the solid line for different flow rates.

Using this boundary condition also did not show predicted increases in the effluent concentration for increasing numbers of tablets and showed the concentration decreasing from using two tablets to three as shown in Figure 61.

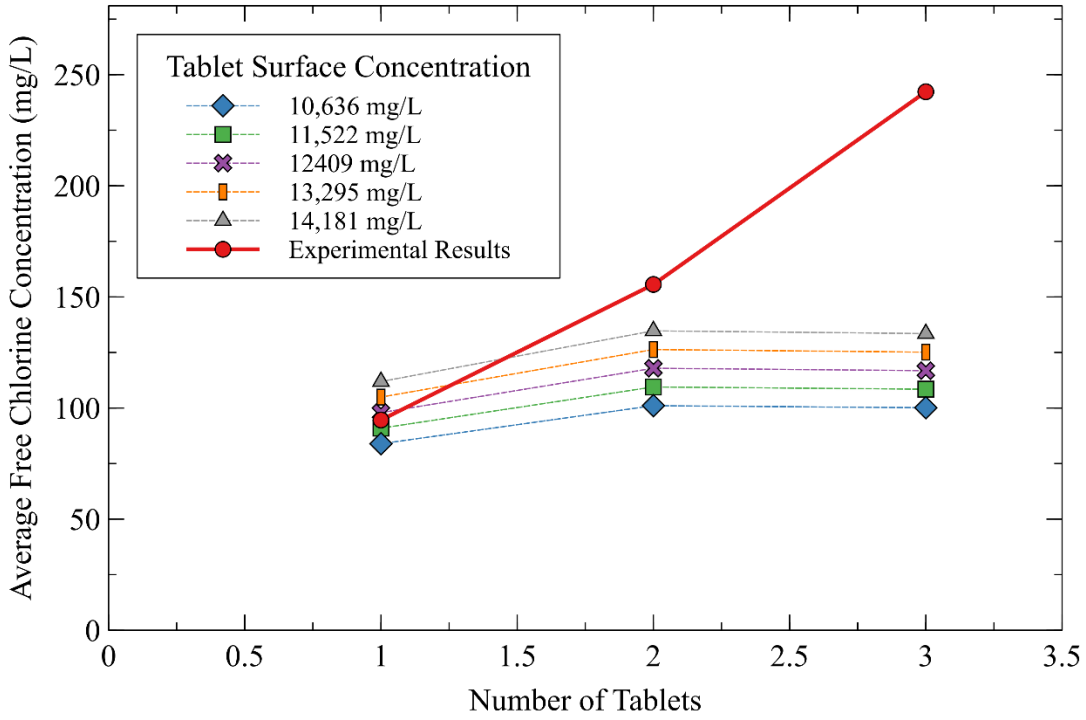

Figure 61. Comparison of concentrations calculated by COMSOL using a constant concentration boundary condition for the tablet in the dashed lines and measured in the lab in the solid line for different numbers of tablets.

Seeing this was not a good way to represent the boundary between the solid tablet and the water flowing through the chlorinator, the boundary condition was changed to a constant flux boundary. Similar to the analysis above, different values of flux were used by doing a parameter sweep for a model that was represented in all the experimental data sets (one tablet, 1.16 gpm flow rate, outlet at bottom left). The flux was converted to a mass rate using the available surface area of the tablet. To get the expected effluent concentration of 94.2 mg/L, the mass rate would need to be set at 2,440 mg/min. This value is much higher than the predicted mass dissolution rates using experimental results. This is likely

due to the change from the 3D behavior to the 2D models which have much less surface area representing the tablet.

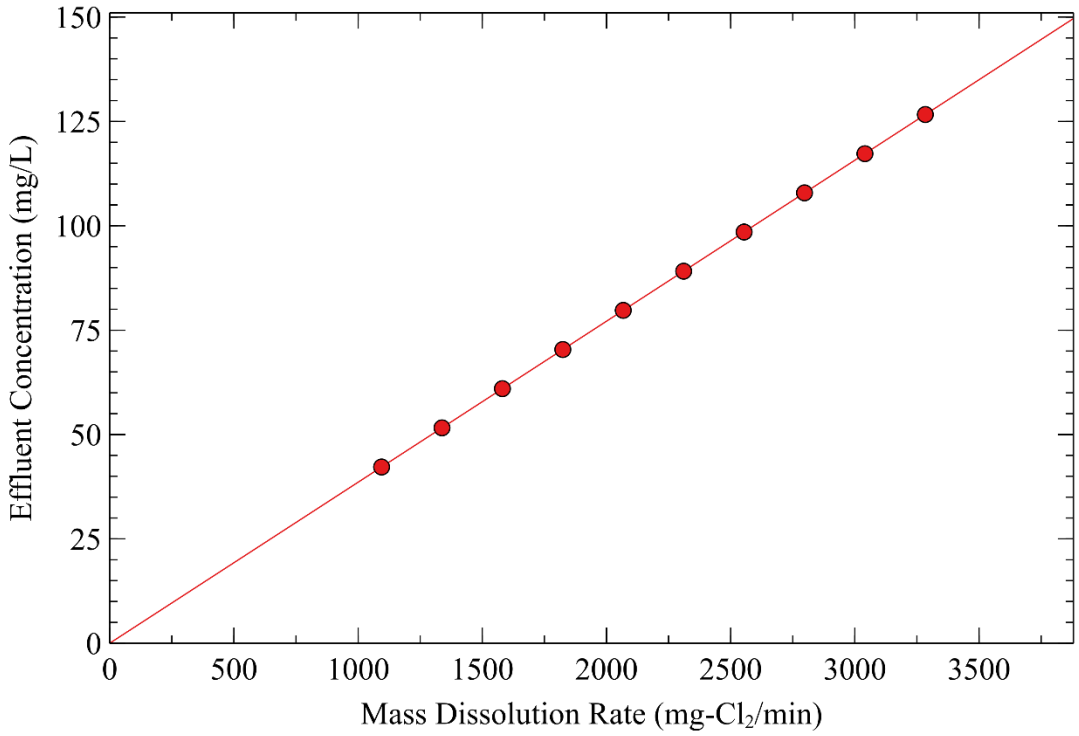

Figure 62. Effluent concentrations calculated by COMSOL using a constant flux of chlorine at the boundary representing the tablet surface.

Mass rates in this range (1,642 mg/min to 2,737 mg/min) were then swept along with the different flow rates used in the experiments to produce the plot in Figure 63 where the different dashed lines represent the different mass rates used and the solid red line is the experimental results.

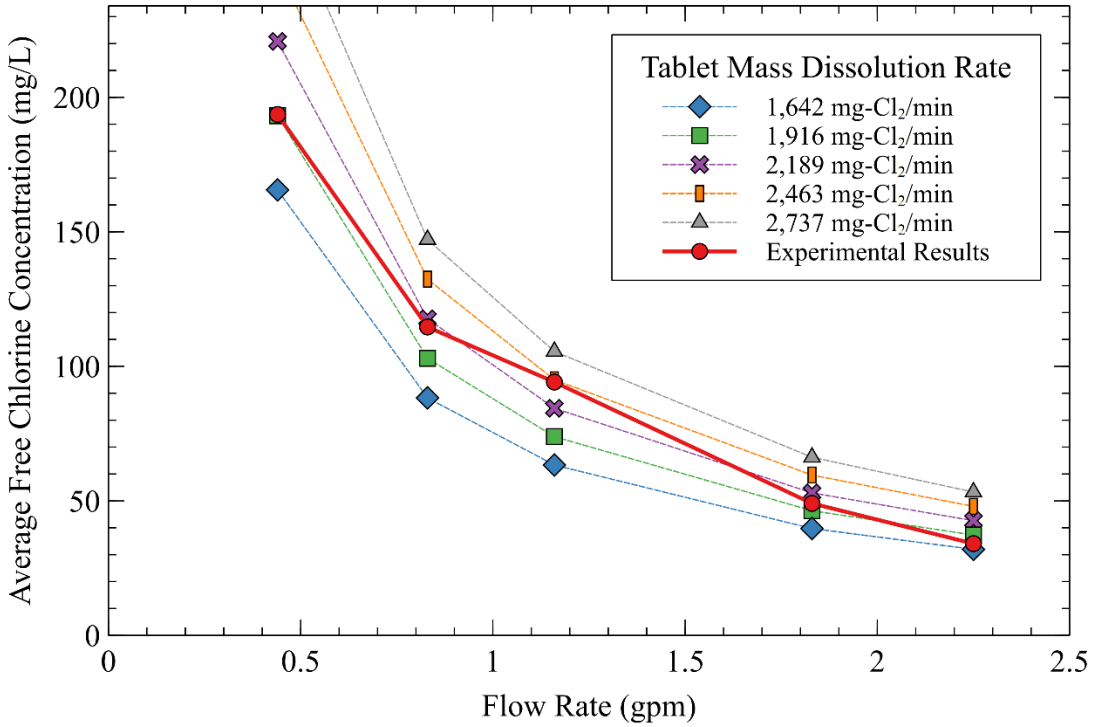

Figure 63. Comparison of concentrations calculated by COMSOL using a constant flux of chlorine at the boundary representing the tablet surface in the dashed lines and measured in the lab in the solid line for different flow rates.

The process was repeated using 1, 2 and 3 tablets in the model and the same dissolution mass rates in Figure 63. These showed an increase in effluent concentration for an increase in tablet number, but not as great as the experimental results. This was likely due to the fact that the flux was calculated using the surface area of just one tablet. An increase in tablet number in 3D would result in a greater increase in available surface area than in the 2D models so it makes sense that the results for two and three tablets are lower than expected in the models. Again, the different dashed lines represent the different mass rates used and the solid red line is the experimental results.

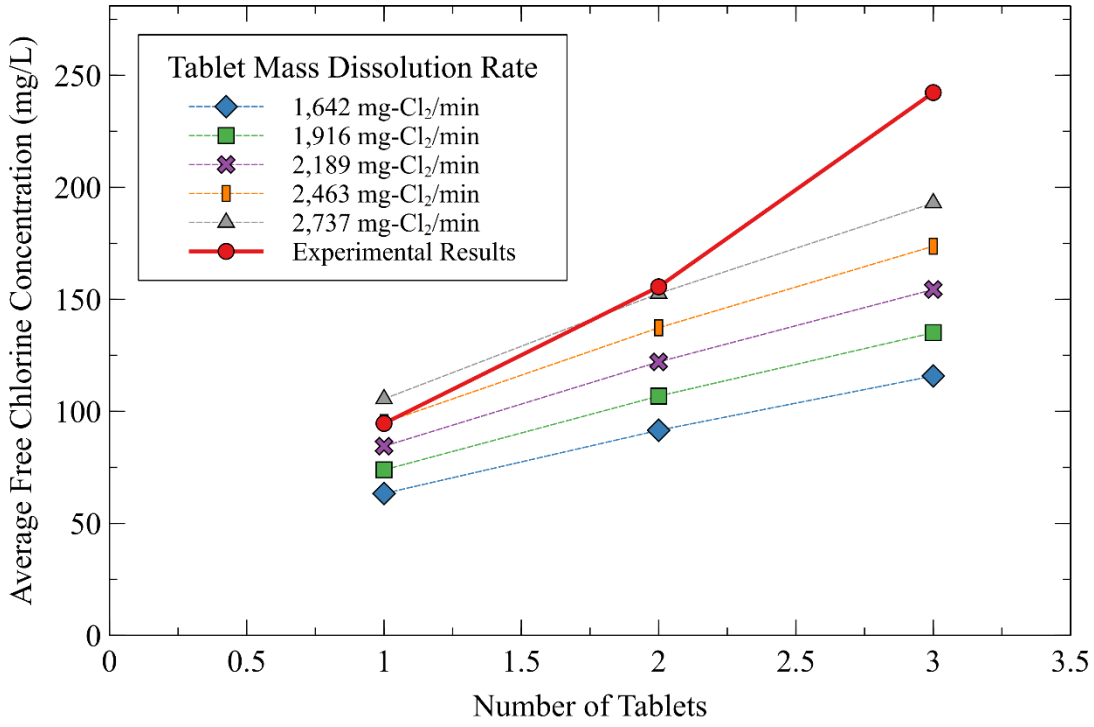

Figure 64. Comparison of concentrations calculated by COMSOL using a constant flux of chlorine at the boundary representing the tablet surface in the dashed lines and measured in the lab in the solid line for different numbers of tablets.

This process was completed one more time to compare the effluent concentrations for the different outlet locations. Results for this modeling can be seen in Figure 64 and 65 differed from the experimental results for additional outlet locations modeled.

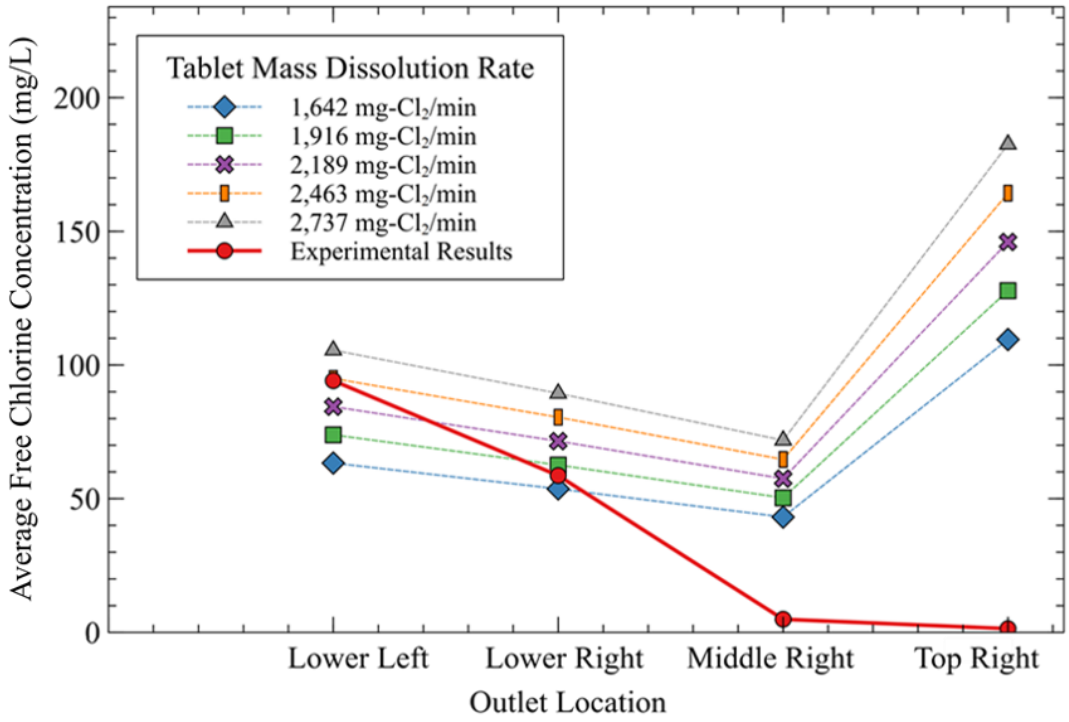

Figure 65. Comparison of concentrations calculated by COMSOL using a constant flux of chlorine at the boundary representing the tablet surface in the dashed lines and measured in the lab in the solid line for different outlet locations.

This evaluation showed that the model was not sufficient for modeling the correct behavior for the different outlet locations as the highest effluent concentration was shown for the top right outlet location. This configuration resulted in the lowest effluent concentration in the experimental results. In order to help explain this, the concentration profiles for each geometry were plotted using COMSOL to help understand what could be happening. These profiles can be seen in Figure 66 with each outlet location represented twice with different ranges for concentration.

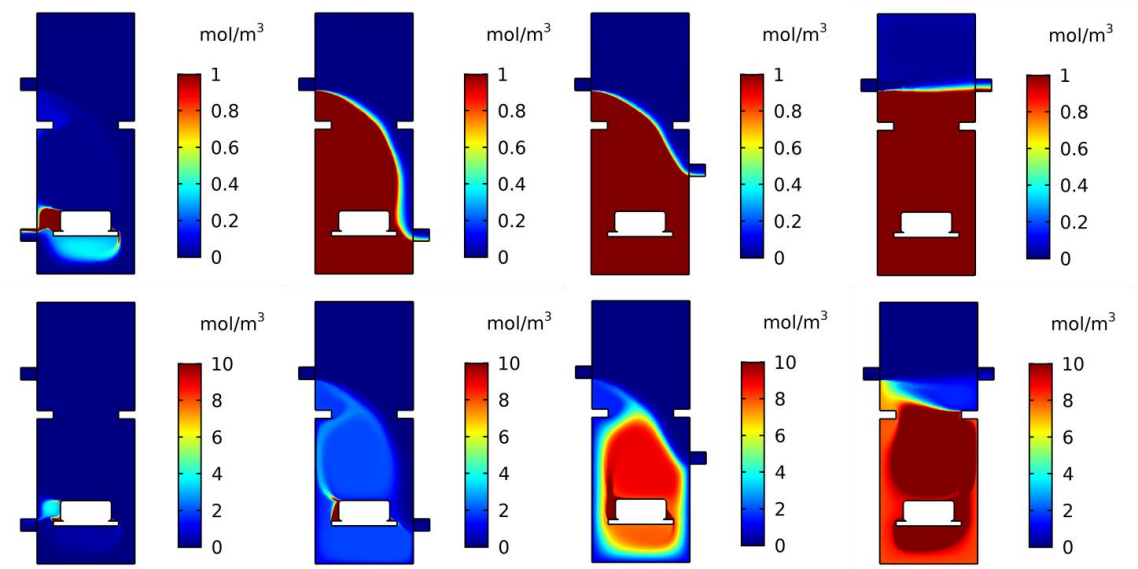

Figure 66. Concentration profiles for the different outlet locations modeled shown with ranges from 0 to 1 mol/m^3 and 0 to 10 mol/m^3.

The images on the top row show a range from 0 to 1 mol/m^3 and the images on the bottom are from 0 to 10 mol/m^3. The purpose of showing two different ranges was to give an idea of what the overall concentration gradient looked like in the chlorinator using the larger range and to show the boundary between the highly concentrated regions of the chlorinator and the flow path from the inlet to the outlet as represented in the lower range concentration images. It appears that the top right outlet location resulted in the highest effluent concentration because the flow path was able to "pick up" a lot of the chlorine concentration located in the concentrated region directly below the flow path. In the other geometries, less chlorine was present in the effluent because not as much was moved out through the main flow path from the inlet to the outlet.

These images also show that as the tablet dissolves, the concentration fills the area where it is not disrupted by the main flow pattern and is fairly evenly distributed throughout the bottom portion of the chlorinator body for the middle right and top right outlet locations.

Something that has been largely ignored in this thesis is the flakes of tablet that were observed leaving the tablet and settling on the bottom of the chlorinator. An example of these flakes can be seen in Figure 67. These flakes have been ignored for all analysis, but it is plausible they contain some percentage of available chlorine. While more studies would need to be done to prove that the concentration remains higher at the bottom of the chlorinator due to the flakes that come off the tablet as it is dissolving, it is likely this is a big reason that the model and experimental behavior do not line up for these outlet locations. This does not present as large of a problem for the bottom left outlet location because there is a high flow rate thorough the portion of the chlorinator where these flakes settle giving them less of an effect on the overall results.

Figure 67. Flakes of the tablet accumulating at the bottom of the chlorinator.

4.3.2. Study 2: Effect of Varying Diffusion Coefficient

As mentioned in the Methods and Materials for this study, an exact diffusion coefficient was not known for the species released from the tablet. To understand the importance of the diffusion coefficient value on the results of the model, the model was run using several different diffusion coefficients. First, the model was run with all of the standard settings for adjustable parameters: a flow rate of 1.16 gpm, one tablet, the outlet on the bottom left, and a constant flux boundary condition at the tablet's surface of 0.035 mol/(m^2·s). The diffusion coefficient was swept for eleven values between 1×10^{-10} and

$1x10^{-8}$ m^2/s and the results can be seen in Figure 68. This plot shows that there was some variation in the effluent concentration when the diffusion coefficient was changed, but any differences were very small at less than 1 mg/L. This gave confidence that even though the precise diffusion coefficient was unknown, the value used was not greatly affecting the modeling results.

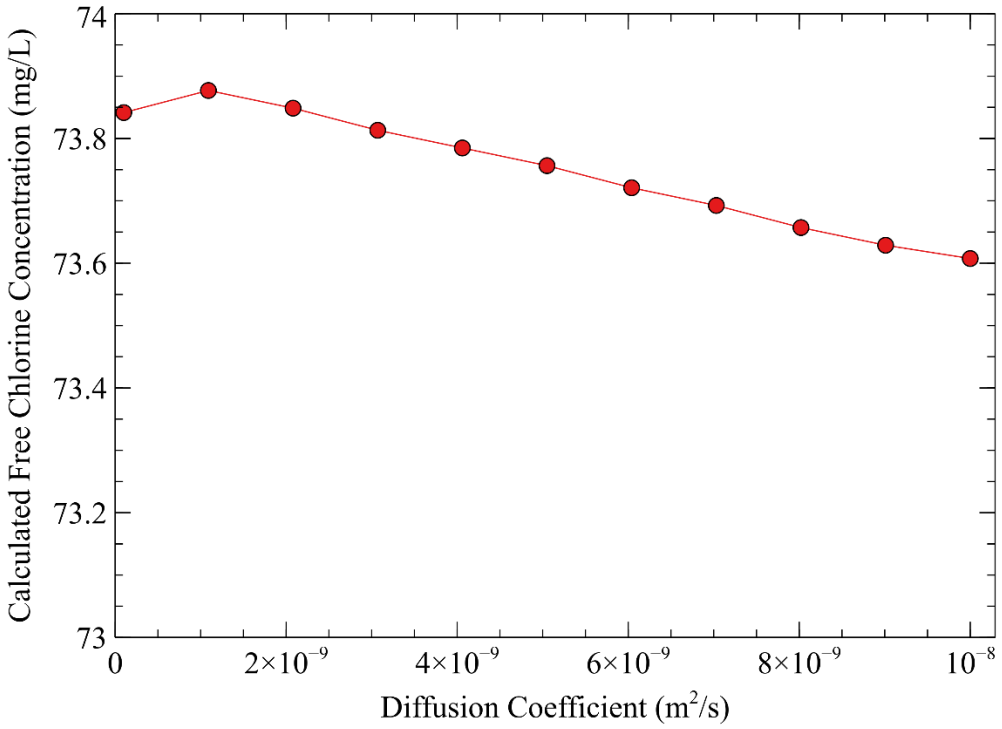

Figure 68. Computational model results for free chlorine concentration at the outlet of the chlorinator when different diffusion coefficients were used for the tablet.

4.3.3. Study 4: Analysis of Flow Paths

Lastly, flow paths were analyzed to help make sense of some of the results seen in Objective 2. When evaluating different flow rates and number of tablets effects on the free chlorine concentration leaving the chlorinator, it was determined that the mass flux from the tablet is most likely constant. However, this conclusion did not make sense when looking at the results for different outlet locations because if it were true, it would be expected that the outlet concentration would be the same regardless of the location of the outlet. While changes in flow rate did not cause a difference in the dissolution rate, these results made it clear that flow through the chlorinator does matter for the concentration of chlorine present in the effluent. To better understand this, flow paths were plotted using COMSOL for the different outlet locations tested and can be seen in Figure 73.

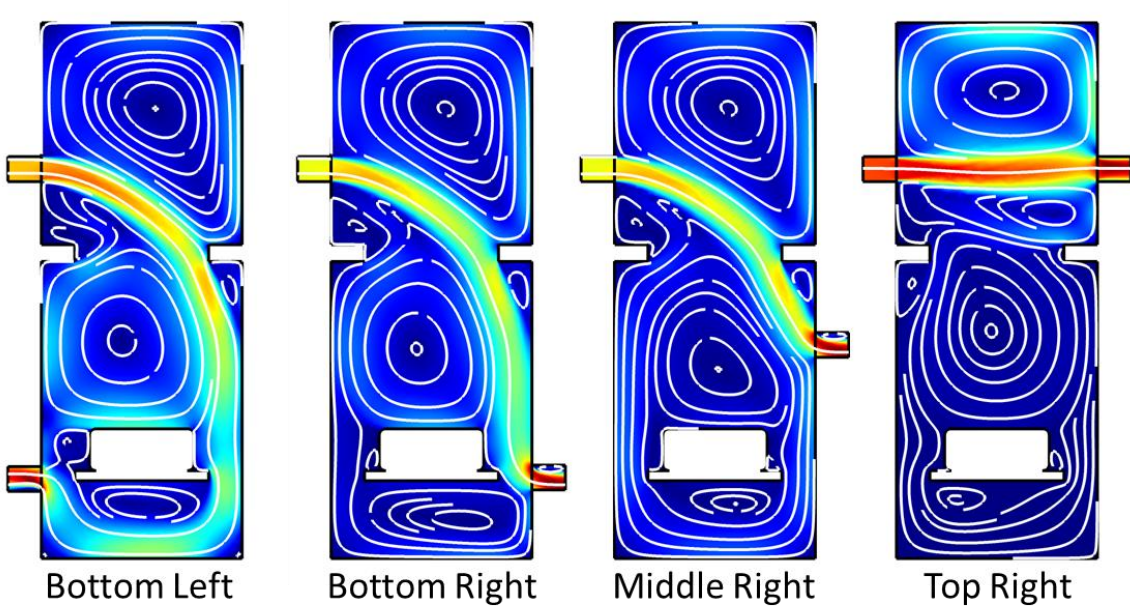

Figure 69. Flow paths for each of the outlet locations plotted on top of the velocity profile in the chlorinator. Outlet locations are labeled below each image.

As seen in the figure, the bottom left flow pattern goes around the tablet and under the basket before exiting the chlorinator. The bottom right flow pattern flows next to the tablet before exiting the chlorinator. The middle and top right outlet locations result in flow patterns that stay above the tablet while traveling though the chlorinator body. The main difference in the flow patterns seems to be the disruption of the bottom half of the chlorinator by the main flow profile and higher surface velocity along the tablet. Especially in the middle right and top right outlet locations, the bottom portion of the chlorinator is one large eddy. Seeing the results, it makes sense that these eddies play a large role in how much mass leaves the chlorinator. The bottom left outlet location has the best opportunity to break up the eddies seen in the other geometries because a large majority of its flow goes through the location where these eddies are shown to exist. This again brings up the question of the effects of the flakes of tablet that settle at the bottom of the chlorinator body seen in Figure 67. The main question about these flakes is if they contain a significant amount of available chlorine and if so, do they increase the chlorine concentration at the bottom of the unit. If this is the case, we would expect much higher concentrations for flows that encounter the bottom of the chlorinator body like the bottom left and bottom right outlet locations do.

Another hypothesis that could help explain the consistency of chlorine concentration in the chlorinator effluent is that the basket has a larger effect on the flow patterns than anticipated either by blocking flow from reaching the sides of the tablet or by keeping the higher velocity flow closer to the tablet for longer. Models were run with an

added 2D representation of the basket and the resulting flow paths can be seen in Figure 70.

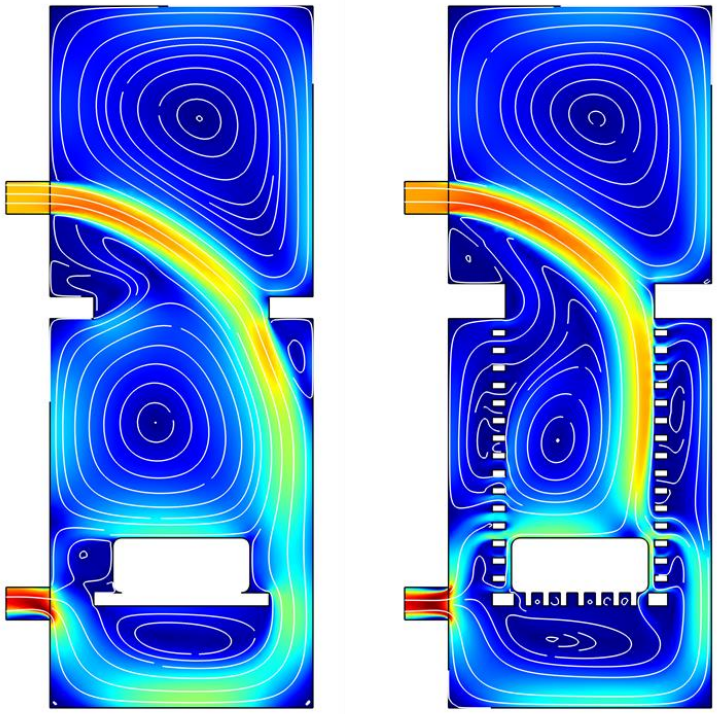

Figure 70. Flow paths and velocity profiles of models run with and without the effect of a basket holding the chlorine tablet.

From the flow patterns, some differences between the models can be seen. There appears to be more flow around the top and left side of the tablet when the basket is introduced and it also helps to break up some of the eddies that are seen in the model without the basket. Another important thing to look at for these models were how the concentration profiles within the chlorinator were affected by the change which is shown in Figure 71. It appears that more concentrated regions of the chlorinator change between the two models where it moves from the left side of the tablet without the basket and to the

bottom of the chlorinator with the basket again supporting that flow through the bottom portion of the chlorinator below the basket is important.

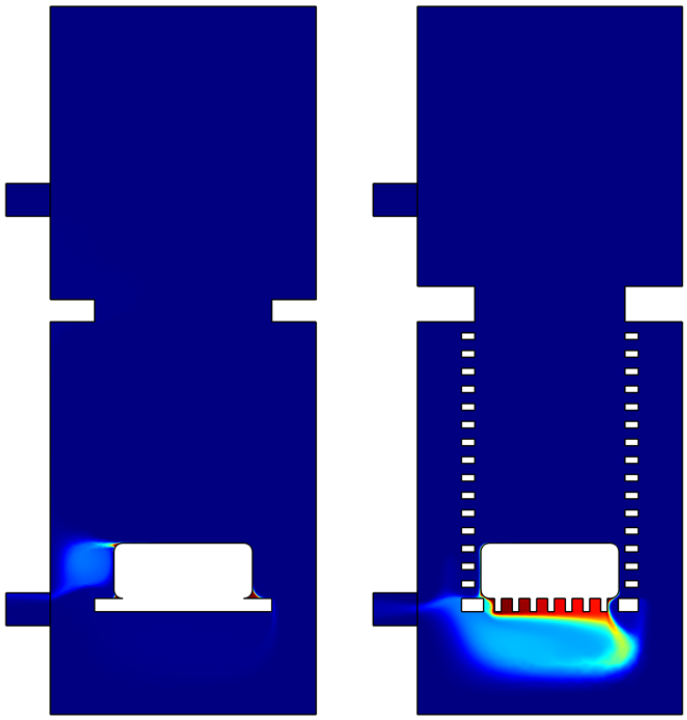

Figure 71. Concentration profiles of models run with and without the effect of a basket holding the chlorine tablet.

5. CONCLUSIONS

The overarching goal of this research was to characterize the relationship between chlorine tablet dissolution and the hydrodynamics of the chlorinator used in the Cange water system. This included investigating the effects of flow rate, number of chlorine tablets used, and inlet/outlet location on the chlorinator body using both CFD modeling and laboratory experiments.

The first method of achieving this involved developing a CFD model to represent the existing tablet chlorinator. This model provided initial insights to the behavior of tablet dissolution in the chlorinator and gave enough evidence through the analysis of different inlet and outlet locations that further study of the chlorinator was warranted to ensure operation that avoided variability in the amount of chlorine introduced to the system. These models supported the hypothesis that flow through the chlorinator would cause the chlorine mass transfer rate to decrease as the tablet gets smaller resulting in a decreasing effluent concentration over time. Results showed that the rate at which chlorine was leaving the chlorinator from the tablet generally had a large increase when flow began followed by a sharp decrease that trailed off as the tablet dissolved. All inlet and outlet locations modeled resulted in this sort of behavior except for when the inlet and outlet were both located at a position that would result in a low velocity at the surface of the chlorine tablet. This occurred when the inlet and outlet produced a flow path that did not interfere directly with the bottom portion of the chlorinator where the tablet was sitting. In this configuration, the chlorine level over time was relatively stable with little variation likely due to the effects

of diffusion throughout the chlorinator. There were many assumptions and simplifications in these models; however, the results helped to design the experiments performed in the lab.

Taking the results from the initial modeling, experiments were performed using a replica chlorinator in a controlled lab setting to further evaluate the chlorinator performance. This included observing dissolution time of a chlorine tablet and determining the effects of inlet and outlet locations, flow rate, and number of tablets on the concentration of chlorine leaving the system over time. It was hypothesized that if the chlorine tablet dissolution is controlled heavily by both diffusion and convection, both flow rate and inlet/outlet location would affect the mass rate of chlorine leaving the chlorinator. It was also hypothesized that using a higher number of tablets will lead to a higher chlorine concentration due to the larger exposed surface area for tablet dissolution.

The first experiment involved observing a tablet dissolving in a bucket of water. The results of this experiment showed that the tablet took around 15.5 hours to completely dissolve. This information was used to help design the experiments where the tablet was dissolved using flow through the chlorinator. The results showed close to constant dissolution of the tablet, but dissolution did slow towards the end of the experiment. This could have been due to the decreased surface area of the tablet, but also could have been affected by the increase in chlorine concentration in the surrounding water. The tablet in this experiment dissolved at an average rate of 413 mg/min. This value represents the total mass lost from the tablet, not just the mass of chlorine lost to the water.

The next experiment looked at the effects of flow rate through the chlorinator. Instead of seeing a large peak of chlorine concentration followed by a decline over time as the tablet dissolved, the concentration leaving the chlorinator was remarkably steady as the tablets dissolved around 50% over the 7-hour test period. The premise that decreasing concentrations in the effluent of the chlorinator was what was thought could be a reason in the variability of chlorine concentrations seen at the fountains in the Cange water system and this behavior was supported by the initial models, but not the experimental data. It was shown that as flow rate increases, the expected concentration in the effluent decreases due to dilution effects of the increased amount of water passing through the chlorinator. The relationship determined between the expected concentration of the effluent and the flow rate through the chlorinator was found to be best represented with a power law function if the tablet dissolved at a constant mass rate. Data fell along this predicted function leading to the conclusion that, for this outlet location, the tablet dissolution rate is constant regardless of the flow rate around it or the velocity at the tablet's surface. The average mass dissolution rate found for these experiments was 345 mg-Cl_2/min with a standard deviation of 46 mg/min and a coefficient of variation of 0.13.

The next experiment looked at the number of tablets used in the chlorinator and results supported the hypothesis that an increase in the number of tablets would result in an increase in the concentration of the effluent. This relationship was found to be linear, but not a one to one increase meaning that using double the amount of tablets does not lead to double the concentration likely due to the fact that when tablets are stacked, surface area exposed to the flow is lost. The experiments using different number of tablets supported

that the mass dissolution rate when the outlet is at the bottom left is constant over the test period. The average mass dissolution rate for a single tablet was calculated using two different methods and assuming a constant mass flux. The measured values from the lab fell between the two estimations. The first method was to calculate the dissolution rate and divide by the number of tablets used and resulted in a mass dissolution rate of 370 mg-Cl_2/min with a standard deviation of 39 mg/min and a 0.11 coefficient of variation. The second method was to calculate the dissolution rate using the available surface area of the tablets when stacked. This resulted in a dissolution rate of 438 mg-Cl_2/min with a standard deviation of 34 mg/min and a 0.08 coefficient of variation. The actual dissolution rate should be somewhere between these two reported values.

The last experiment for the second objective of this research was to determine the effects of outlet location and the concentration of the effluent. The configurations predicted to result in the most consistent concentrations due to the low flow velocity at the tablet surface resulted in very little chlorine leaving the chlorinator. This data set showed that the mass rate of chlorine leaving the chlorinator was not completely independent of flow as different flow patterns resulted in different concentrations of chlorine leaving the system. The differences in mass of the tablets from the beginning to end of dissolution also showed that there was a difference in the amount they had dissolved during the course of the experiment based on the outlet location with the trend following the idea that the geometries resulting in low flow velocity over the tablet's surface lost the least amount of mass during the experiment. The differences were not a large as the differences seen in measured chlorine concentrations of the effluent meaning the tablet was still dissolving at

a rate close to the rate of the tablets in the other experiments. This meant that the additional mass of the tablet and the available concentration associated with it must be remaining in the bottom of the chlorinator and not diffusing throughout as previously predicted that it would. This led to the conclusion that the flow pattern, rather than flow rate is one of the most important parameters in determining the mass dissolution rate of the tablet and how much chlorine will leave the chlorinator.

Lastly, the CFD chlorinator models were refined to fit the experimental data from the experiments performed and were used to gain a better understanding of the behavior of the fluid and chlorine mass transport. It was hypothesized that models showing low flow velocity through the bottom portion of the chlorinator will correspond to the outlet locations that had low chlorine concentrations in the experimental results.

Several updates were made to the initial models, perhaps the most influential being the change from low-velocity (laminar) to high-velocity (turbulent) flow. This changed the level of mixing and dispersion of chlorine throughout the chlorinator. Another important change was modeling the boundary representing the surface of the chlorine tablet using a constant flux. An appropriate flux found for modeling the chlorinator behavior was 0.035 mol/(m^2·s). Based on the surface area of a tablet, this value correlates to a mass dissolution rate of 1916 mg-Cl_2/min. This is much higher than the dissolution rates predicted using the experimental data and is likely due to the simplification from 3D to 2D models which have much lower surface areas representing flux from the tablet.

Models fit the experimental data well for the effects of different flow rates, but not as well for the results showing different numbers of tablets and outlet locations. Outlet location concentration values calculated using COMSOL resulted in the highest concentrations for the outlet location that had the lowest concentration in the experimental results. To help explain this, flow patterns were analyzed.

Models that had an outlet allowing flow to dip down into the bottom half of the chlorinator resulted in much higher concentrations. Models without this dip, such as the ones with the outlet towards the top of the chlorinator, showed large, slow eddies in the bottom half of the chlorinator that limited mass transfer. An additional model was also produced that showed the effects of the basket on the flow through the chlorinator. Adding the basket resulted in increased surface velocity on all sides of the tablet and increased the concentration shown below the basket in the model. This supports the conclusion that a flow pattern through this bottom portion of the chlorinator is important for preventing stagnant areas containing high chlorine concentration.

Overall, the conclusions drawn from both the experimental data and computational models seems to point to the original chlorinator design with the inlet towards the top of the chlorinator and the outlet directly below the inlet towards the bottom of the chlorinator body being the most appropriate configuration of inlet and outlet locations. In this configuration, mass dissolution rate of any number of tablets was shown to be nearly constant regardless of flow rate, and the flow pattern in this geometry seems to be the most efficient in assisting mass transfer out of the chlorinator. There were two thoughts behind why this behavior may have occurred. The first was that the tablet has reached a maximum

dissolution rate in this configuration and regardless of the flow it cannot dissolve any faster with higher flow rates like we would expect. Another thought is that the tablets are chemically designed to dissolve at a steady rate regardless. Based on the results of these experiments, it appears that even submerged the tablets release a steady amount of chlorine. Regardless of the reason, because of the way the tablets were shown to dissolve makes the chlorinator simple to operate in practice with any flow rate moving through the side stream of the main system for chlorination resulting in the same overall system chlorine level. Using various numbers of tablets can assist in scaling up or down the concentration in the water system based on the requirements of the system. The work presented in this thesis supports that the manner in which chlorine tablets dissolve in the chlorinator designed for the Cange water system is not a likely cause of the variations in chlorine seen throughout the system. Some other possible reasons for this are listed in the final section of this thesis.

6. FUTURE WORK

There is still much work to accomplish as an extension of this project. There are many, many more parameters that could be tested using the laboratory model of the chlorinator like using a different brand of tablets, changing the inlet location, or running longer tests to name just a few. Longer tests would help determine the timeframe tablets should be used and when they should be replaced. It is my hope that future CEDC students will take on this project and continue learning about the nuances of tablet dissolution to develop WASH solutions for the most vulnerable groups around the world.

In addition to lab work, there are many improvements that could be made to the computational models. It seems the best way of pinning down exact values like the diffusion coefficient, concentration at the surface of the tablet, and mass dissolution rate of the tablet would be to utilize the optimization module built into COMSOL. To truly get a model accurate to real life, a 3D model may also need to be developed. Lastly, it would be advantageous to reincorporate the moving mesh into the model to predict long term behavior. If the tablet truly is dissolving at a constant rate, this mesh may be simpler than the moving mesh used in the early models of this report, moving as a function of time rather than flux and area. Another option is to evaluate changes in tablet size using a parameter sweep; each step of the sweep could be run as a steady-state case. The system is quazi-steady state because changes in flow happen much more quickly than changes in tablet size.

There is also work that could be done overall to strengthen the Cange Municipal Water System. This could include a further optimization of the entire system to minimize costs and ensure standards at the points of delivery are met. These optimizations could include determining optimal pump operation, valve control and system operation (Mala-Jetmarova et al., 2017). Something else to consider is determining how to optimize chlorine disinfection to maintain uniform chlorine residual throughout the distribution system. Munavalli and Kumar discuss the process of determining appropriate chlorine dosage subjected to minimum and maximum constraints. This is a complex process, but can ensure microbial integrity of the water, control taste and/or odor problems and hinder formation of carcinogenic disinfection by-products (Munavalli & Mohan Kumar, 2003).

Lastly, more could be done to understand the water quality in Cange. Understanding the chlorine demand and how it changes over the course of a year would go a long way in ensuring safe water is delivered. A more rigorous testing protocol could be put into place for a short time to ensure all residual requirements are met throughout the system and maintained over a 24-hour period after water is collected from a fountain.

There is still a lot of work that could be done in this area of research to better understand calcium hypochlorite dissolution and its implications for water disinfection. I am reminded of a Haitian proverb that many Haitians will use to end reports that states, “little by little a bird builds it’s nest.” While living in Haiti, I thought it was a little silly, but after working on this thesis, I now agree that it is the perfect way to end a report. Little by little all of this work came together that will hopefully benefit people in some way, little by little the Cange water system becomes stronger, little by little more people worldwide

gain access to basic WASH infrastructure, and little by little we come closer to a world with universal and equitable access to safe and affordable drinking water for all.

Piti piti, zwazo fè nich.

7. REFERENCES

American Water Works Association (AWWA). (2006). Water Chlorination/ Chloramination Practices and Principles. In *AWWA Manual M20* (Second Edi). https://www.awwa.org/Portals/0/files/publications/documents/M20LookInside.pdf

Axiall Water Treatment Products. (2013). *Accu-Tab System*. www.accu-tab.com

Betcher, S. (2007). Calcium Hypochlorite Tablet Chlorination: Fact or Fiction? *Water Quality Products*, 24–26. www.SENSAFE.com

Blair, S., Jooste, D., Bryant, D., Ashkar, C., Burt, S., Ngo, T. T., Wolf, D., Kuwahara, K., & Peterson, J. (2016). Humanitarian engineering opportunities and challenges in rural Dominican Republic: A case study of El Cercado. *GHTC 2016 - IEEE Global Humanitarian Technology Conference: Technology for the Benefit of Humanity, Conference Proceedings*, 709–716. https://doi.org/10.1109/GHTC.2016.7857356

Brikké, F., & Bredero, M. (2003). *Linking technology choice with operation and maintenance in the context of community water supply and sanitation*.

Cassivi, A., Guilherme, S., Bain, R., Tilley, E., Waygood, E. O. D., & Dorea, C. (2019). Drinking water accessibility and quantity in low and middle-income countries: A systematic review. *International Journal of Hygiene and Environmental Health*, *222*(7), 1011–1020. https://doi.org/10.1016/j.ijheh.2019.06.011

Centers for Disease Control and Prevention (CDC). (2014). *Chlorine Residual Testing Fact Sheet*.

Centers for Disease Control and Prevention (CDC). (2018). *Global Health - Haiti: Increasing Access to Improved Water and Sanitation*. https://www.cdc.gov/globalhealth/countries/haiti/what/water-and-sanitation.html

Central Intellegence Agency (CIA). (2020). *Central America :: Haiti*. The World Factbook. https://www.cia.gov/library/publications/the-world-factbook/geos/print_ha.html

Churchill, A. A., Ferranti, D., Roche, R., & Walters, A. A. (1987). *World Bank Discussion Papers: Rural Water Supply and Sanitation Time for a Change*.

Clark, M. M. (2009). *Transport Modeling for Environmental Engineers and Scientists* (Second Edi). John Wiley & Sons, Inc.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2012). *Water Treatment Principles and Design* (Third Edit). John Wiley & Sons, Inc.

Curtis, V., Cairncross, S., & Yonli, R. (2000). Review: Domestic hygiene and diarrhoea - Pinpointing the problem. In *Tropical Medicine and International Health* (Vol. 5, Issue 1, pp. 22–32). John Wiley & Sons, Ltd. https://doi.org/10.1046/j.1365-3156.2000.00512.x

Dowell, S. F., Tappero, J. W., & Frieden, T. R. (2011). Public Health in Haiti — Challenges and Progress. *New England Journal of Medicine*, *364*(4), 300–301. https://doi.org/10.1056/NEJMp1100118

Dubois, L. (2012). *The Aftershocks of History*. Picador.

Gelting, R., Bliss, K., Patrick, M., Lockhart, G., & Handzel, T. (2013). Water, Sanitation and Hygiene in Haiti: Past, Present, and Future. *Am. J. Trop. Med. Hyg*, *89*(4), 665–670. https://doi.org/10.4269/ajtmh.13-0217

Gordon, A., Plumblee, J., & Vaughn, D. (2017). Developing Rural Water Systems: An Evaluation of Haiti's First Chlorinated Municipal Water System in the Central Plateau. *Journal of Humanitarian Engineering*, *5*(1).

Greene, D. J., Farouk, B., & Haas, C. N. (2004). CFD design approach: For chlorine disinfection processes. *Journal / American Water Works Association*, *96*(8), 138–150. https://doi.org/10.1002/j.1551-8833.2004.tb10685.x

Greene, D. J., Haas, C. N., & Farouk, B. (2006). Computational Fluid Dynamics Analysis of the Effects of Reactor Configuration on Disinfection Efficiency. *Water Environment Research*, *78*(9), 909–919. https://doi.org/10.2175/106143005X72984

HACH. (2014). *Free Chlorine DPD Method*.

Haider, H. (2006). Disinfection Techniques of Rural Water Supplies. *Journal of Pakistan Engineering Congress*, *42*(June 2006), 1–16.

Haiti Libre. (2012). Haiti - Social : First chlorinated municipal water system, in the Central Plateau. *Haiti Libre*. https://www.haitilibre.com/en/news-5980-haiti-social-first-chlorinated-municipal-water-system-in-the-central-plateau.html

Hannoun, I. A., & Boulos, P. F. (1997). Optimizing distribution storage water quality: A hydrodynamic approach. *Applied Mathematical Modelling*, *21*(8), 495–502. https://doi.org/10.1016/S0307-904X(97)00043-7

Harp, D. L. (2002). Current Technology of Chlorine Analysis for Water and Wastewater. In *Technical Information Series: Vol. Booklet No*.

Hodges, S. D. (2019). *Effects of Contact Suface Area and Tangential Velocity on the Dissolution of Tableted Calcium Hypochlorite* [Letourneau University]. https://doi.org/10.1017/CBO9781107415324.004

Hubbard, B., Lockhart, G., Gelting, R. J., & Bertrand, F. (2014). Development of Haiti's ruralwater, sanitation and hygiene workforce. *Journal of Water Sanitation and Hygiene for Development*, *4*(1), 159–163. https://doi.org/10.2166/washdev.2013.089

Hutton, G., Haller, L., & Bartram, J. (2007). Global cost-benefit analysis of water supply and sanitation interventions. *Journal of Water and Health*, *5*(4), 481–501. https://doi.org/10.2166/wh.2007.009

Johnson, J. B., Menzel, M. A., Edwards, J. W., Ford, W. M., Johnson, J. B., Menzel, M. A., Edwards, J. W., & Ford, W. M. (2005). Comparison of Two Systems for Chlorinating Water in Rural Honduras. *Journal of Health, Population and Nutrition*, *23*(3), 931–936.

Joint Monitoring Progamme (JMP). (2017a). *Joint Monitoring Program Wash Data 2017*. https://washdata.org/data/household#!/

Joint Monitoring Progamme (JMP). (2017b). *Progress on Drinking Water, Sanitation and Hygiene Update and SDG Baselines*. http://apps.who.int/bookorders.

Kidder, T. (2003). *Mountains Beyond Mountains*. Random House.

King, A., & Cole, B. (2008). *Haiti Map and Satellite Image*. Geology.Com. https://geology.com/world/haiti-satellite-image.shtml

Kremer, M., Null, C., Miguel, E., Nber, A., & Peterson, Z. (2008). *Trickle down: Diffusion of chlorine for drinking water treatment in Kenya*.

Leverenz, H., Darby, J., & Tchobanoglous, G. (2006). *Evaluation of Disinfection Units for Onsite Wastewater Treatment System*. www.PDH-Pro.com

Life. (1997). The Millennium: The 100 Events Headline, No. 46: Water Purification. *Life Magazine, Special Double Issue*.

Liu, L., Oza, S., Hogan, D., Chu, Y., Perin, J., Zhu, J., Lawn, J. E., Cousens, S., Mathers, C., & Black, R. E. (2016). Global, regional, and national causes of under-5 mortality in 2000–15: an updated systematic analysis with implications for the Sustainable Development Goals. *The Lancet*, *388*(10063), 3027–3035. https://doi.org/10.1016/S0140-6736(16)31593-8

Mala-Jetmarova, H., Sultanova, N., & Savic, D. (2017). Lost in optimisation of water distribution systems? A literature review of system operation. In *Environmental Modelling and Software* (Vol. 93, pp. 209–254). Elsevier Ltd. https://doi.org/10.1016/j.envsoft.2017.02.009

Meyer, E. (2004). Water, Chemistry and Public Health. In Associate Chimie et Eau (Ed.), *Chemistry for Water Perspectives and Recommendations* (pp. 91–99).

Ministere de la Sante Publique et de la Population (MSPP). (2011). *Rapport de Cas Journalier et Cumulatif Données Preliminaries*.

Moriarty, P., Smits, S., Butterworth, J., & Franceys, R. (2013). Trends in Rural Water Supply: Towards a Service Delivery Approach. *Water Alternatives*, *6*(3), 329–349. www.water-alternatives.org

Munavalli, G. R., & Mohan Kumar, M. S. (2003). Optimal scheduling of multiple chlorine sources in water distribution systems. *Journal of Water Resources Planning and Management*, *129*(6), 493–504. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:6(493)

NSF International, World Health Organization (WHO), & Pan American Health Organization. (1998). *Providing Safe Drinking Water in Small Systems: Technology, Operations, and Economics* (J. A. Cotruvo, G. F. Craun, & N. Hearne (eds.)).

Orner, K. D., Calvo, A., Zhang, J., & Mihelcic, J. R. (2017). Effectiveness of in-line chlorination in a developing world gravity-flow water supply. *Waterlines*, *36*(2), 167–182. https://doi.org/10.3362/1756-3488.16-00016

Pan American Health Organization (PAHO). (2013). *REPUBLIC OF HAITI NATIONAL PLAN FOR THE ELIMINATION OF CHOLERA IN HAITI 2013-2022*.

Pan American Health Organization (PAHO). (2018). *Epidemiological Update Cholera Summary of the situation*. https://bit.ly/2Hp3C97

Pan American Health Organization (PAHO). (2020). *Haiti reaches one-year free of Cholera*. https://www.paho.org/en/news/23-1-2020-haiti-reaches-one-year-free-cholera

Patrick, M., Berendes, D., Murphy, J., Bertrand, F., Husain, F., & Handzel, T. (2013). Access to Safe Water in Rural Artibonite, Haiti 16 Months after the Onset of the Cholera Epidemic. *Am. J. Trop. Med. Hyg*, *89*(4), 647–653. https://doi.org/10.4269/ajtmh.13-0308

Pickering, A. J., Crider, Y., Amin, N., Bauza, V., Unicomb, L., Davis, J., & Luby, S. P. (2015). Differences in field effectiveness and adoption between a novel automated chlorination system and household manual chlorination of drinking water in Dhaka, Bangladesh: A randomized controlled trial. *PLoS ONE*, *10*(3), 1–16. https://doi.org/10.1371/journal.pone.0118397

Reid, K. (2019). *2010 Haiti earthquake: Facts, FAQs, and how to help*. World Vision. https://www.worldvision.org/disaster-relief-news-stories/2010-haiti-earthquake-facts

Rivera, S., & Matousek, R. (2015). On-site Generation of Hypochlorite - Overview. In *AWWA Manual M65* (pp. 1–9).

Taflin, C. (2006). A low-cost solution to rural water disinfection: The development of an effective chlorinator. *IEEE Engineering in Medicine and Biology Magazine*, *25*(3), 36–37. https://doi.org/10.1109/MEMB.2006.1636349

Tappero, J., & Tauxe, R. (2011). Lessons Learned during Public Health Response to Cholera Epidemic in Haiti and the Dominican Republic. *Emerging Infectious Diseases*, *17*(11), 2087–2093. https://doi.org/10.3201/eid1711.110827

The World Bank. (2020). *Haiti Overview*. https://www.worldbank.org/en/country/haiti/overview#1

UN-Water. (2018). *Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation*.

UN-Water. (2019). *United Nations World Water Development Report 2019: "Leaving no one behind."* https://en.unesco.org/sites/default/files/wwdr_2019_main_messages.pdf

UNICEF. (2019). *Drinking Water Data*. https://data.unicef.org/topic/water-and-sanitation/drinking-water/#

United Nations. (2010). The human right to water and sanitation. *General Assembly*, *64*(292), 3. http://www.un.org/es/comun/docs/?symbol=A/RES/64/292&lang=E

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development A/RES/70/1*.

Wang, H., & A. Falconer, R. (1998). Simulating disinfection processes in chlorine contact tanks using various turbulence models and high-order accurate difference schemes. *Water Research*, *32*(5), 1529–1543. https://doi.org/10.1016/S0043-1354(98)80014-6

Westlake Chemical, & Axiall. (2020). *Calcium Hypochlorite Tablets Safety Data Sheet*.

World Health Organization (WHO). (1996). Chlorine in Drinking Water. In *Guidelines for drinking-water quality* (2nd ed.). World Health Organization. https://www.who.int/water_sanitation_health/water-quality/guidelines/chemicals/chlorine.pdf?ua=1

World Health Organization (WHO). (2003). *Constraints affecting the development of the water supply and sanitation sector*. https://www.who.int/docstore/water_sanitation_health/wss/constraints.html

World Health Organization (WHO). (2016). *Chlorine monitoring at point sources and in piped distribution systems. Fact Sheet 2.30.*

World Health Organization (WHO). (2017). *Safely managed drinking water - thematic report on drinking water 2017*. https://doi.org/ISBN 978 92 4 156542 4

APPENDICES

APPENDIX A: FIELD WATER QUALITY DATA COLLECTION IN THE CANGE MUNICIPAL WATER SYSTEM

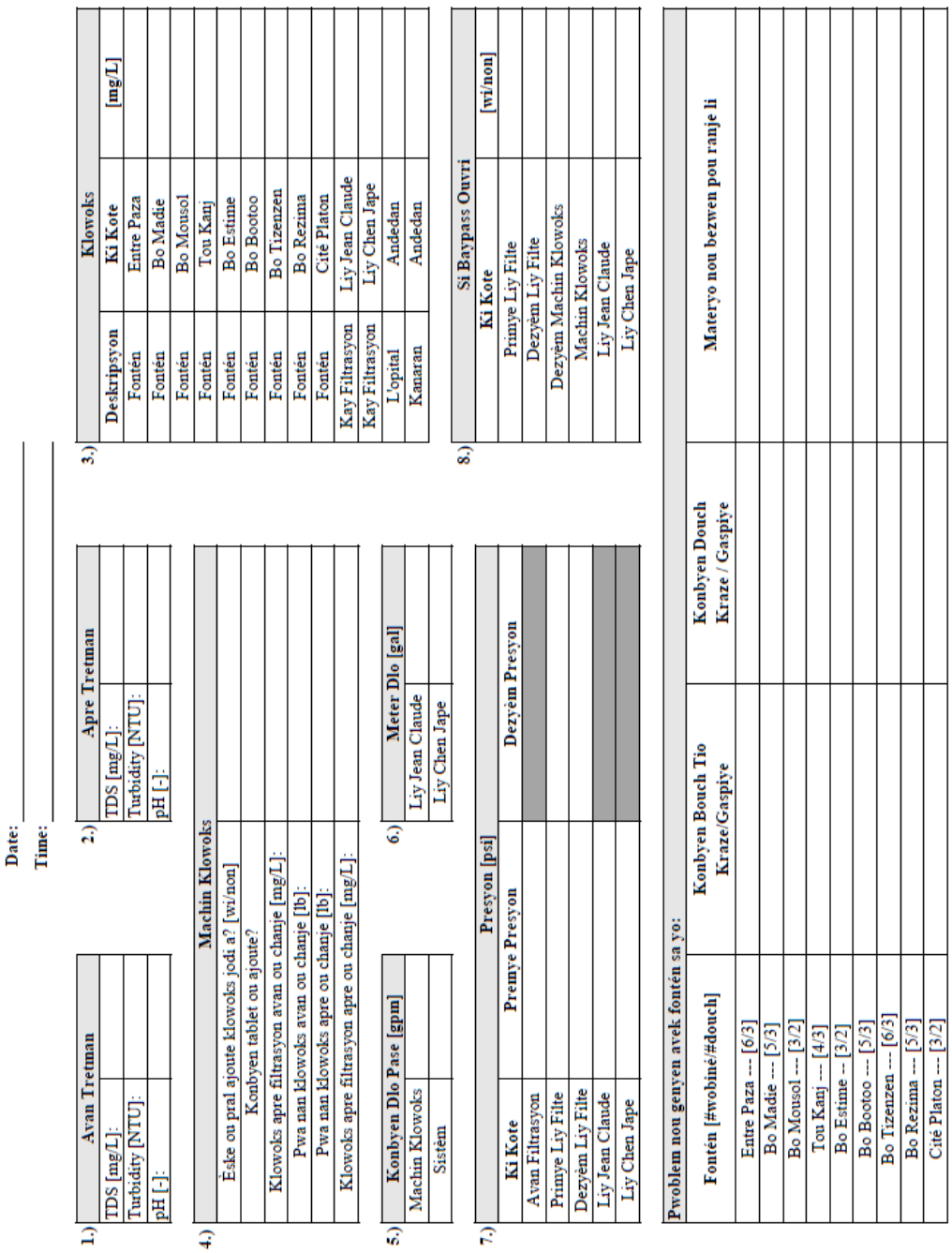

Figure 72. Data collection sheet for water quality field data from the Cange Water System in Haitian Creole.

Above is the data collection sheet for field data collection used for the Cange Water System. Values recorded using this resource (listed as number listed on data collection sheet in Figure 77) include:

1.) TDS, turbidity, and pH of the source water before any treatment has taken place

2.) TBS, turbidity, and pH after the water has been filtered and chlorinated

3.) Free chlorine residual concentrations at the eight water system fountains throughout Cange, the two pipes leaving the treatment building connected to the cisterns, and two locations on the Zamni Lasante compound.

4.) Information about the chlorinator including if chlorine tablets were added that day, how many tablets were added, the weight of chlorine in the chlorinator before and after any addition, and the chlorine concentration in the main line before and after any addition.

5.) The total system flow rate and the flow rate through the chlorinator.

6.) Water meter reading of the two water lines leaving the treatment building (one feeds to the village, one to the Zanmi Lasante compound)

7.) Pressure readings before and after filtration and in the lines leaving the treatment building.

8.) A recording of which valves of the treatment system are open. Options include the filters, the chlorinator, the system set up in case the chlorinator fails, and the two lines leaving the treatment building.

9.) The last table is a place to record any problems with any of the fountains in the village and what the expected needs to fix it will be.

In order to compile this data more easily, it is recorded and saved on a local computer in a folder that is linked to the Google Cloud platform. Data is uploaded as long as internet is available. A python script was developed in order to easily compile the data in a singe table. Note, the file location would need to be changed if running this file on a different computer. The simplest way is to copy the path to a folder containing all desired Excel files. The script can be found on the next page of this appendix.

```
import glob
import pandas as pd

filenames = glob.glob('C:\\Users\\ashle\\Desktop\\Water Data\\*.xlsx')

df = pd.DataFrame()

for f in filenames:
    file = pd.read_excel(f, header = None)
    file.to_csv(f, encoding = 'utf-8')
    df.loc[f,0] = file.loc[0,4]
    df.loc[f,1] = file.loc[1,4]
    df.loc[f,2] = file.loc[4,2]
    df.loc[f,3] = file.loc[5,2]
    df.loc[f,4] = file.loc[6,2]
    df.loc[f,5] = file.loc[4,5]
    df.loc[f,6] = file.loc[5,5]
    df.loc[f,7] = file.loc[6,5]
    df.loc[f,8] = file.loc[5,9]
    df.loc[f,9] = file.loc[6,9]
    df.loc[f,10] = file.loc[7,9]
    df.loc[f,11] = file.loc[8,9]
    df.loc[f,12] = file.loc[9,9]
    df.loc[f,13] = file.loc[10,9]
    df.loc[f,14] = file.loc[11,9]
    df.loc[f,15] = file.loc[12,9]
    df.loc[f,16] = file.loc[13,9]
    df.loc[f,17] = file.loc[14,9]
    df.loc[f,18] = file.loc[15,9]
    df.loc[f,19] = file.loc[16,9]
    df.loc[f,20] = file.loc[17,9]
    df.loc[f,21] = file.loc[10,4]
    df.loc[f,22] = file.loc[11,4]
    df.loc[f,23] = file.loc[14,4]
    df.loc[f,24] = file.loc[12,4]
    df.loc[f,25] = file.loc[13,4]
    df.loc[f,26] = file.loc[17,2]
    df.loc[f,27] = file.loc[18,2]
    df.loc[f,28] = file.loc[17,5]
    df.loc[f,29] = file.loc[18,5]
    df.loc[f,30] = file.loc[22,2]
    df.loc[f,31] = file.loc[23,2]
    df.loc[f,32] = file.loc[23,4]
    df.loc[f,33] = file.loc[24,2]
    df.loc[f,34] = file.loc[24,4]
    df.loc[f,35] = file.loc[25,2]
    df.loc[f,36] = file.loc[26,2]
```

APPENDIX B: REYNOLDS NUMBER CALCULATIONS

Table 6. Reynold's number calculation results for each flow rate used in the experiments as well as the average flow rate through the chlorinator in the Cange Municipal Water System.

Flow Rate, Q (gpm)	Area of Inlet, A (m^2)	Flow Velocity, v (m/s)	Pipe Diameter, D (m)	Fluid Density, ρ (kg/m^3)	Dynamic Viscosity, μ (kg/m-s)	Reynold's Number Re
0.44	2.77E-04	0.100	1.88E-02	998.2	1.002E-03	1,873
0.83	2.77E-04	0.189	1.88E-02	998.2	1.002E-03	3,534
1.16	2.77E-04	0.264	1.88E-02	998.2	1.002E-03	4,939
1.83	2.77E-04	0.416	1.88E-02	998.2	1.002E-03	7,791
2.25	2.77E-04	0.512	1.88E-02	998.2	1.002E-03	9,579
5.50	2.77E-04	1.251	1.88E-02	998.2	1.002E-03	23,416

Calculations were based on the flow in the inlet pipe to the chlorinator which has a diameter of 0.742 in. Properties for water at 20°C were found from Clark, 2009. A sample calculation for 0.44 gpm flow rate is as follows:

$$v = \frac{Q}{A} = \frac{\frac{0.44\ gal}{min} \times \frac{m^3}{264.172\ gal} \times \frac{min}{60\ s}}{\pi \times \left(\frac{0.742\ in}{2} \times \frac{m}{39.37\ in}\right)^2} = 0.100 \frac{m}{s}$$

$$D = 0.742\ in\ \times \frac{m}{39.37\ in} = 1.88 \times 10^{-2}\ m$$

$$Re = \frac{\rho v D}{\mu} = \frac{\frac{998.2\ kg}{m^3} \times \frac{0.100\ m}{s} \times 1.88 \times 10^{-2}\ m}{\frac{1.002 \times 10^{-3}\ kg}{m \times s}} = 1{,}873$$