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OPTIMIZING CHLORINE DISINFECTION BY CHLORINE INJECTION LOCATION AND PIPE DIAMETER SELECTION IN A WATER DISTRIBUTION SYSTEM

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OPTIMIZING CHLORINE DISINFECTION BY CHLORINE INJECTION LOCATION AND PIPE DIAMETER SELECTION IN A WATER DISTRIBUTION SYSTEM

By

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Table of Contents

List of figures

List of tables

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List of abbreviations

Cl – Chlorine (mg/L)

Ct – Concentration multiplied by time (min*mg/L)

EPA – Environmental Protection Agency

MINSA – Ministerio de Salud del Peru – The Peruvian Ministry of Health

NGO – Non-Governmental Organization

WHO – World Health Organization

Abstract

Due to a variety of factors chlorination is common water disinfectant for community-scale distribution systems. The town of Suyo, Peru was already equipped with a gravity fed water system and drip chlorinator which achieved 4-log inactivation of viruses throughout the town, however, it was not providing 3-log inactivation of giardia cysts at all points of the system.

This project used an EPANET model to determine and compare the potential benefits of changes which could be made to the pre-existing water system in Suyo.

The model was used to compare current operating conditions of the Suyo system, 1.5 mg/L chlorine addition at the reservoir, with different potential operating configurations. To determine if there was a more efficient concentration of chlorine addition or point of chlorination, chlorination of different concentrations taking place at the reservoir and six other points between the reservoir and the town were modeled as well as the potential to chlorinate at two points simultaneously. To increase the amount of time the chlorine had to react with the water, the pipe between the reservoir and the town was modeled at different diameters.

Replacing the pipe between the reservoir and the town from the current 4” to 8” was found to raise Ct values and achieve 3-log giardia inactivation throughout the town. No benefit was found in moving the point of chlorination closer to the city nor in chlorinating both at the reservoir and at an additional node. Increasing the concentration of chlorination was found to provide 3-log giardia inactivation to a larger percentage of the town but did not provide full coverage for all users.

1 Introduction

Since the acceptance of the germ theory of disease, clean drinking water has been widely recognized as one of the most fundamental and effective strategies to ensure and improve the health of a population. In the past few decades tremendous strides have been taken to improve the situation worldwide. In 2005 95.8% of the world's urban and 75.7% of the rural population were using improved drinking water, water from a source protected from contamination. By 2017 this had increased to 96.4% in urban areas and 84.5% in rural (UNSD 2018). As the most basic water demands are met more and more countries, communities, and individuals are looking for ways to improve preexisting water systems.

The primary goals of a water treatment system are 1) that it should improve the quality and or accessibility of water and 2) that the system must be sustainable, able to be operated and maintained by the community after construction without dependence on outside sources of funding. Sustainability is an often overlooked concern for projects in the developing world where it is arguably even more important as financial aid from governments and non-governmental organizations (NGOs) can be less dependable due to increased political instability (Johnson et al. 2008). If these outside sources are cut off when the community is unable to sustain the system themselves, then there are good odds the project will break down, resulting in nothing more useful than a waste of resources. For example, a town in Peru had most of a brand new water treatment plant built to utilize multiple basin filtration which was abandoned before completion when changes in the political landscape caused funding to be diverted to other projects. Less obvious problems include failing to provide adequate training to operators and lack of community investment (Smith 2011).

To reduce these risks and provide value to preexisting systems, project planners should consider the possibilities of a modular approach by which a system is planned and then constructed one part at a time with each completed stage able to function and improve the community even if subsequent stages fall through.

This paper focuses on one such strategy, the efficacy of alternatives to improving chlorination disinfection in a preexisting piped water system. However, as different strategies may be more effective in different situations this introductory section will begin with a review of other potential treatment options.

1.1 Water Treatment in the Developing World

Water treatment systems can be broadly classified by the location where treatment occurs. Point-of-use treatment occurs in the location, typically the home, where the water is to be used. Point-of-use treatments have the benefits that they reduce the likelihood that the water will be recontaminated between treatment and consumption. They can be very inexpensive and may be the only option for populations in remote areas. The main weakness is the strong educational component required. All people who will be treating water must be properly educated to ensure that no well-meaning mistakes are made. Solar disinfection and boiling are methods which work better for point-of-use treatment than in a larger scale system.

Solar disinfection (SODIS) is accomplished by placing clear water in a clear container, usually a bottle of polyethylene terephthalate (PET) plastic, and placing it in the sun for 6 hours or multiple days if there is cloud cover. The disinfection is two-fold: a combination of UV irradiation and the disinfection achieved by heating the water. For the heating component to be effective, the water temperature must be raised above the optimum microbial growth temperature. The process can also be hampered by turbidity which partially blocks irradiation and decreases the efficiency of disinfection (Vivar et al. 2017). This is a time consuming process and can be difficult to teach. One large scale version using photovoltaics was constructed to simultaneously treat water and generate electricity (Jin et al. 2016).

Boiling is the process of heating the water beyond what the harmful microbes can survive. This is very effective and widely practiced in Peru as a point-of-use treatment (Clasen et al. 2008).

Large scale systems are those which provide water to communities larger than a family group. Treatment takes place at a central location from which the water is transferred to individual consumers. This transfer can be provided by a piped system leading to individual houses or communal taps or water can be carried in trucks, jugs, or other containers. If the water is not piped directly to the consumer the potential vectors for contamination increase, particularly where containers used to transfer it are unclean or uncovered (Wright et al. 2004). The reliability of the water system is also greatly important. One study of two Uganda water systems showed that if supply was disrupted, incidence of cryptosporidium and rotavirus would skyrocket. The same trend was observed in E. coli but to a lesser degree (Hunter et al. 2009).

When there is no contamination between the treatment and the consumers, these systems provide a much greater ease of use for the consumers. Large scale systems also have the advantage that they are easier to maintain and inspect to ensure correct function.

Filtration and chlorination can be effective treatment strategies in both point-of-use and large scale situations. Filtration involves passing water through a semi-porous media which destroys or inactivates pathogens usually through the development of a biological layer but more modern filters may make use of colloidal silver impregnated ceramics. To increase sustainability, locally available filtration media are preferred. Perhaps the most basic form of filtration is to use the natural properties of the earth by building a well or pumping water out from the ground (Sharma and Amy 2009, Ahmed et. al. 2017). Traditional slow sand filters rely on sand and pebbles. Biochar, created through burning locally available organics such as farm wastes, has also been shown to be effective, dependent on their pore size and capacity, for the removal of inorganics and heavy metals, anionic contaminants, radionuclides, and arsenic (Gwenzi et al. 2017). Nonsynthetic filters are associated with low material costs and high labor requirements while still being attainable for a community.

1.2 Chlorination in the Developing World

Solid form chlorine (granular or tablet) is widely popular in the developing world due to its availability, effectiveness, cost, and relative ease of transportation and use. Chlorine interacts with water to produce hypochlorous acid, HOCl. A second reaction then forms between H^+ and hypochlorite ion OCl^-. HOCl and OCl^- are known as ‘free chlorine’. The concentration of free chlorine remaining in the water after initial disinfection is the chlorine residual (Ratnayaka et al. 2017). Residual chlorine continues to provide disinfection in the water system, reducing the risks of recontamination between treatment and consumption.

$$Cl^2 + H_2O = HOCl + HCl$$

$$HOCl = H^+ + OCl^-$$

Other substances present in the water can also interact with chlorine, reducing the amount of free chlorine produced thereby reducing disinfection efficiency. Ammonia will react with chlorine to form monochloramine NH_2Cl, dichloramine $NHCl_2$, and trichloramine NCl_3. NH_2Cl and $NHCl_2$ are known as ‘combined chlorine’ and are significantly less effective disinfectants than free chlorine. Organic compounds, common in surface waters, will interact to form disinfection byproducts which are hazardous to human health such as chloroform and haloacetic acids (Ratnayaka et al. 2017).

1.2.1 Drip Chlorination

Drip chlorinators consist of a tank holding a chlorine solution, most frequently created by mixing granular chlorine with water, which drips down into a water reservoir before the contained water flows into the water system. Depending on the residence time, a drip chlorinator may improve disinfection by allowing the chlorine more time to react with the water.

1.2.2 In-Line Chlorination

In-line chlorinators add chlorine to water as it moves through the pipe. One method of accomplishing this is to add a chamber containing a chlorine tablet to the pipe. As the water flows over the tablet it erodes, releasing chlorine into the water. These systems are inflexible. They are constructed to meet expected flow rates. If flow rates change later there is no way to adjust it afterwards.

Even when the flow rate is steady, which is by no means guaranteed, the erosion of the tablet is irregular (Yoakum, 2013). Research has demonstrated that much of this unreliability can be improved by proper storage of the tablets. If kept in individual water-tight wrapping until use, relatively consistent chlorination with free chlorine concentrations of less than 0.2 mg/L could be achieved. If exposed to humidity beforehand however, they dissolved much more quickly resulting in high concentrations during the first day and almost nothing on subsequent days. The residual chlorine concentration could be increased with the use of multiple tablets, but the effects only lasted for the first day (Orner 2011).

Similar results were found by a point-of-use study of a combination of filtration through a colloidal-silver-impregnated ceramic pot filter followed by chlorination through dissolution of calcium hypochlorite tablets. Chlorine residuals started above 2.5 mg/L on the first day and dwindled to around 0.7 mg/L over the course of the next seven days (Cash-Fitzpatrick et al. 2008).

Alternatively, chlorine powder could be mixed into a liquid solution and attached to the pipe on the downstream side of an orifice plate. The pressure differential between the two sides of the plate creates a vacuum which then draws the liquid into the pipe. Such a system can be surprisingly inexpensive to construct (Schuhmann and Karlheim 2012). The resultant hydrodynamic cavitation has been found to increase disinfection rates and reduce production of chloroform when used in conjunction with a sodium hypochlorite solution (Wang et al. 2015). It is unknown whether there has been any study into the long-term durability of these systems.

1.2.3 Diffusion Chlorination

Diffusion chlorinators function similarly to the in-line tablet chlorinators in that they consist of solid chlorine disbursed into water through erosion. Chlorine tablets are placed in a porous container which is then suspended below the water level in a reservoir. As with drip chlorination this can provide longer disinfection times.

1.3 Water Treatment in Peru

In January of 1991, cholera swept through South America. By the end of December 321,334 cases and 2,906 deaths had been reported in Peru alone (Ries et al. 1992) with a total of 533,000 cases and 4,700 deaths across the 19 countries affected (Swerdlow et al. 1992). Analyses of the epidemic showed a strong correlation between infection and drinking unboiled water, drinking water stored in contaminated containers, and eating or drinking items prepared in uncontrolled conditions such as street stalls. It has even been theorized that the warmer conditions of an El Nino year may have contributed by making the environment more hospitable for the cholera bacteria (Tickner and Gouveia-Vigeant 2005, Fraser 2009). This theory is supported by a study showing a 200% increase in hospital admission for diarrheal illness in children under 10 during the 1997 – 1998 El Nino (Checkley et al. 2017). It is also frequently attributed to lack of chlorination and poor sanitary conditions.

At the time, a study of some of the municipal wells and private water taps in the city of Piura found that a majority of those sampled had no residual chlorine (Reis et al. 1992). The city of Trujillo had no chlorination at all (Swerdlow et al. 1992).

The water treatment situation in Peru has greatly improved sine 1991 although much improvement is still needed. In 2015, 95% of the Peruvian urban population and 72% of the rural population were using an improved drinking water source (WHO 2016).

1.3.1 Rural Water Systems

Peruvian communities of fewer than 2,000 people are required to manage and maintain their own water system through the direction of a committee of six local volunteers elected for two-year terms by the community. At least two members of this committee must be female. All members are elected at the same time which sometimes results in a complete loss of knowledge of how to manage the system. Most communities reduce this risk by paying a permanent water operator to handle repair and maintenance. The committee itself is responsible for sharing information with and getting input from the community, collecting the monthly water fee paid by each household attached to the water system, and coordinating larger-scale repairs and annual maintenance work days.

These committees are in turn overseen by the Area Technica Municipal (ATM) who works out of the district municipality. In the district of Suyo there were over 60 town and annexes, many of which were difficult to get to. With limited transportation options this can result in practically no oversight or assistance to towns further away.

Many water systems are originally constructed with funds from the Peruvian government or an NGO. Operation and maintenance costs, as well as any wages paid to the operator, are paid by the committee from the monthly water fees. When the system requires repairs beyond the committee's ability to pay they must either collect a one-time additional payment from the community members or apply to the district municipality or an NGO for aid. There is frequently a lack of training for operators and committee members alike.

1.3.2 Chlorination in Peru

Peruvian water quality limits are stipulated by MINSA (the Ministerio de Salud, ministry of health) in the Reglamento de la Calidad De Agua Para Consumo Humano (MINSA 2011). Chlorine regulation consists of two parts: 90% of all measurements of chlorine residual taken throughout the water system must be 0.5 mg/L or above, the remaining 10% cannot be lower than 0.3 mg/L. The minimum water quality regulations mandated by MINSA, the World Health Organization (WHO), and the US Environmental Protection Agency (EPA) are shown in Table 1-1 below.

Table 1-1. *Minimum Water Quality Regulations (MINSA 2011) (WHO 2017) (EPA 2018)*

	Peru MINSA	**WHO**	**EPA**
Chlorine Residual Min (mg/L)	90% ≥ 0.5 10% ≥ 0.3	≥ 0.2 (≥ 0.5 in high risk circumstances)	
Chlorine Residual Max (mg/L)	5	5	4 (as Cl_2)
Thermotolerant Coliforms (mg/L)	0		
Total Coliforms (mg/L)	0		0 (in 95% of monthly samples)
Turbidity (NTU)	≤ 5		≤ 5
pH	6.5 – 8.5		6.5 – 8.5*
Conductivity (µmho/cm)	≤ 1500		
Total Dissolved Solids (mg/L)	≤ 1000		≤ 500*

*Secondary standard

Like the WHO, Peru places the maximum safe limit on chlorine residual in drinking water at 5 mg/L. The EPA uses a 4 mg/L maximum (EPA 2018). Because it is more conservative, 4 mg/L has been used for the purposes of this paper.

1.4 Description of Study Area

Peru is located on the western coast of South America, bordering the Pacific Ocean to the west, Ecuador and Colombia to the north, to the east by Brasil and Bolivia, and to the south by Chile. In 2015, approximately 31,377,000 people lived within its 494,209 square mile area (WHO 2017 and CIA 2018). In 2013 its Gross national income per capita (PPP int. $) was 11, compared to 53 in the United States in the same year. In 2015 life expectancy at birth was 73 and 78 years for men and women, respectively, 4 years lower than in the U.S. (WHO 2017).

Figure 1-1. *A map of Peru with the district of Suyo labeled (from Google Maps).*

The study area was the City of Suyo, in the northern region of Piura. It's location in Peru is shown by the map in Figure 1-1. Suyo sits only a few degrees south of the equator with an annual average temperature of 15 °C which climbs to 29 °C in the summer months. As of the 2007 Census, 11,951 people lived in the district of Suyo. Of these, 985 lived in the capital city, also named Suyo (Suyo 2012). The city of Suyo sits directly on the old panamerican highway, a well-maintained two lane highway which allows easy access to public transportation by taxi and bus to the regional capital city, Piura, to the Southwest and into Ecuador to the North. The Ecuadorian border is 15 minutes by taxi from the city of Suyo. Some towns within the Suyo district are along the highway. Those that are not are connected by dirt roads. As a general rule, the further one moves from the highway the worse the road quality becomes and the more expensive and time consuming transportation is. Spanish is the only language spoken by most residents. Roman Catholic is the predominant faith with an Evangelical presence.

Suyo sits in the foothills of Ayabaca, where the desert of lower Piura begins to transform into mountains. Many communities have spring-fed piped water systems which flow by gravity although towns in the lower elevations may have to rely on pumps and river water. Many systems include pressure-break and purge valves although not all.

1.4.1 Water Quality of Study Area

Owing to its size, the town of Suyo is capable of maintaining a water pump and, therefore, utilizes groundwater for its drinking water. This makes the influent water significantly freer of contamination than the sources used in the rest of the district, surface water, or a protected spring.

Table 1-1-2. *Water Quality of the Suyo Reservoir During Chlorination*

Sampling Location	Reservoir
Date	8/26/2016
Time	7:47 AM
Turbidity (NTU)	2.06
Residual Chlorine (mg/L)	0.11
pH	8.11
Conductivity (µmho/cm)	832
TDS (mg/L)	416
Total Coliforms (CFU/100ml)	0
Thermotolerant Coliforms (CFU/100ml)	0

Water quality sampling was performed for multiple locations in the Suyo district August 24^{th} – 26^{th} of 2016. Table 1.2 contains the water quality measurements of the city of Suyo reservoir after chlorination. Suyo currently employs drip chlorination. Granulated chlorine is mixed with water to form a concentrated chlorine solution stored in a tank above the reservoir with a valve and pipe system to feed the solution into the reservoir. As can be seen from the table, at the time of sampling residual chlorine levels fell below the 0.3 mg/L minimum. Even so, no coliforms were detected. The water temperature was not measured.

2 Methodology

2.1 EPANET Model

A map of the Suyo water system was provided by the Suyo Municipality and transcribed into EPANET, a public domain software created and distributed by the US EPA to model drinking water distribution systems. More information can be found at https://www.epa.gov/water-research/epanet (Rossman 2000) as well as the program available free to download. The original map did not include the reservoir or the full length of the pipe between the reservoir and the town. The reservoir's dimensions were known from previous measurements. The distance between the reservoir and the town was approximated from GPS coordinates of the reservoir and a known point in the town. Six pipe nodes were added in the EPANET model along the pipeline between the reservoir and the town to serve as potential points for the addition of chlorine.

Individual dwellings were not given their own nodes on the model. Instead, a node was placed at the mid-point of each block. Demand for each node was calculated based on the number of homes and businesses fed from that pipeline on the block. This simplification was made to increase clarity of the model and reduce potential for errors when transcribing the data to the model. More specific data from the EPANET model appears in Appendix C.

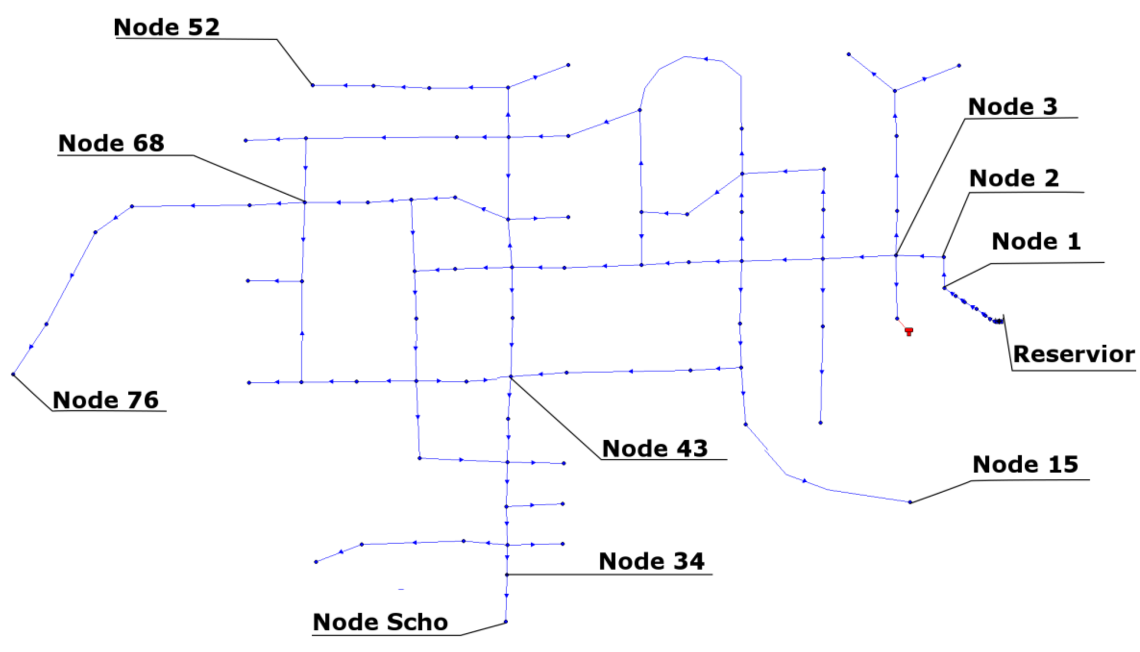

Figure 2-1 *EPANET schematic of the Suyo water system*

EPANET models bulk flow chlorine decay with the following first order reaction:

$$R = K_b * C$$

R = Instantaneous rate of reaction (mg/L/hour)

K_b = Bulk reaction rate coefficient (in this case, -1.0)

C = Reactant concentration (mg/L)

Boundary layer reactions, those taking place along the pipe wall, were modeled using a reaction coefficient of 0 (Rossman 2000).

2.2 Demand

A survey conducted in the neighboring annex of El Jardin in August of 2016 found there to be approximately 4.48 people living in each house; therefore, base demand was calculated from the assumption that 5 people lived in each occupied house. The map of the Suyo water system showed 281 occupied houses. The population was therefore estimated to be 1,405 inhabitants. This figure is believed to be a reasonable estimation of population growth since the 2007 census (Suyo 2012) at which time the Suyo population was 985.

Water consumption per person was assumed to be 90 liters per capita per day (lcd) with a factor of safety of 1.56. These numbers were those used by local engineers building and designing equivalent water systems for populations in the hotter regions of Peru where the majority of the population had flush toilets, as was the case in Suyo. These figures are supported by Twort's demand estimates for developing countries (Ratnayaka et al. 2017).

2.3 Calculation of Ct Value

Calculating the concentration of the chlorine residual times the time it has had to react in the water (Ct) proved to be a challenge as EPANET reports water age from the reservoir to each node on the system but not from one node to another. One cannot, therefore, directly calculate the influence on the Ct value from chlorine added at a node partway through the system.

First, the Ct values for all runs in which all chlorine added was added at the reservoir were calculated as follows:

$$Ctrb = Cb * WArb * 60 \text{ min/hr}$$

Ctrb = Ct value at Point b due to chlorine added at the reservoir (min*mg/L)

Cb = Chlorine concentration at Point b (mg/L)

WArb = Water Age from the reservoir to Point b (hrs)

The system was then used to model different concentrations of chlorine added either at the reservoir or at one of six points between the reservoir and the start of the town (Node 1). These nodes were labeled InA, InB, etc. Their locations are shown in Figure 2-2. The node of chlorination is referred to here as Point a. The node where the chlorine residual was measured is referred to as Point b. Water age from Point a to Point b was calculated by subtracting the water age from the reservoir to Point a from the water age from the reservoir to Point b using the following formula.

$$Ctab = Cb * (WArb - WAra) * 60 \text{ min/hr}$$

Ctab = Ct value at Point b due to chlorine added at Point a (min*mg/L)

Cb = Residual chlorine concentration measured at Point b (mg/L)

WArb = Water Age from reservoir to Point b (hrs)

WAra = Water Age from reservoir to Point a (hrs)

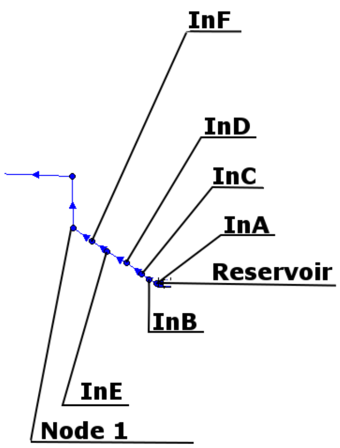

Figure 2-2 *Nodes where chlorine is added and Node 1*

This base value was used to calculate the Ct value for runs where chlorine was added at both the reservoir and at another point. To get the Ct contribution from the chlorine added part way through the system (referred to here as Point a) the chlorine residual concentration was calculated by taking the chlorine residual at the point measured (Point b) when chlorine was being added at both the reservoir and Point a and subtracting what the chlorine residual had been at Point b when chlorine was only being added at the reservoir:

$$Ctrab = Ctrb + ((Cb - Crb) * (WArb - WAra) * 60)$$

Ctrab = Ct value at Point b due to chlorination both the reservoir and Point a (mg*mg/L)

Ctrb = Ct value at Point b when chlorine was only added at the reservoir (min*mg/L)

Cb = Residual chlorine concentration measured at Point b (mg/L)

Crb = Residual chlorine concentration measured at Point b when chlorine was only added at the reservoir (mg/L)

WArb = Water Age from the reservoir to Point c (hrs)

WAra = Water Age from the reservoir to Point a (hrs)

For the purposes of determining the minimum Ct required, the water was assumed to have a constant pH of 8 and a temperature of 10 °C. The minimum required Ct was then determined to be the Ct required for 3-log inactivation of giardia based on the minimum residual concentration found at Node 1 after stabilization.

2.4 Determination of Minimum Required Ct

Because the water in Suyo was 8.11 pH when measured it was assumed to have a pH of 8 for the purposes of determining minimum required Ct.

Water temperature was not measured. As Suyo itself has an average ambient temperature of 15 °C and the water delivered by the Suyo water system was cool to the touch, the minimum required Ct value was based on 3-log inactivation of giardia at 8 pH and an assumed water temperature of 10°C. Ct tables can be found in Appendix B.

Ct values for a 3-log removal of Giardia and a 4-log removal of viruses were available and, therefore, were used in this study to test sufficient removal of both.

2.5 Pipe Size

After modeling a variety of chlorination concentrations at different injection points it was determined that an adequate Ct value to achieve 3-log inactivation of giardia was not being achieved. A series of models were then conducted with different diameters for pipes between the reservoir and Node 3 (shown in Figure 2-1). Node 3 was chosen because it is the first branching node in the system, to prevent pressure build up within the pipeline caused by suddenly shrinking the diameter of the pipe.

2.6 Time to Stabilization

All models were run on the assumption that chlorination would begin at midnight. This is by no means representative of field conditions and was done to ensure that all models could be objectively compared.

Because chlorination began at a time with very low demand, concentration of chlorine residual through the water system is very different in the first few hours than it is for the rest of the run time. For this reason the results section examines only those chlorine residual concentrations and Ct values which occurred after chlorine residuals within the system stabilized to more typical values. 10:00 AM was used as the stabilization time save for a few scenarios studied where the most distant node required more time.

3 Results

3.1 Baseline

As the goal was to improve the performance of the system it was important to first ascertain how the EPANET model would simulate current conditions: 1.5 mg/L chlorine addition at the reservoir. The results appear below in Tables 3.1 – 3.3. Values which fall outside of required ranges have been highlighted.

Table 3-1. *Maximum concentration of chlorine residual after stabilization due to chlorination of 1.5 mg/L at the reservoir.*

Max Chlorine Concentration at Node after Stabilization (mg/L)									***Max All Nodes***
Scho	**76**	**68**	**52**	**43**	**34**	**1**	**2**	**15**	
1.36	1.24	1.37	1.34	1.39	1.37	1.45	1.45	1.4	1.45

Table 3-2. *Percent of hourly residual chlorine measurements which pass Peruvian regulations after stabilization of 1.5 mg/L chlorine addition at the reservoir.*

	≥ 0.5 mg/L	**≥ 0.3 mg/L**
% Residual Measurements after Stabilization	100%	100%

Table 3-3. *Minimum Ct value after stabilization due to 1.5 mg/L chlorination at the reservoir. The minimum Ct required is shown on the table.*

Minimum Ct Value at Node after Stabilization (min*mg/L)									***Min Ct Required (min*mg/L)***
Scho	**76**	**68**	**52**	**43**	**34**	**1**	**2**	**15**	
196	341	175	207	153	185	79	86	138	*168*

As can be seen by these results, current chlorination in Suyo presents no health risks due to over-chlorination and meets Peruvian legal requirements for minimum chlorine residual. However, Ct values are insufficient to achieve 3-log giardia inactivation although they are more than sufficient for 4-log virus inactivation, Ct tables are shown in Appendix B.

3.2 Chlorination at Different Locations

The system was then modeled with chlorine addition taking place at different nodes between the reservoir and the city. As can be seen in Figure 3.1 below, the maximum chlorine residual measured in the water system was only slightly affected by the location where chlorination occurred.

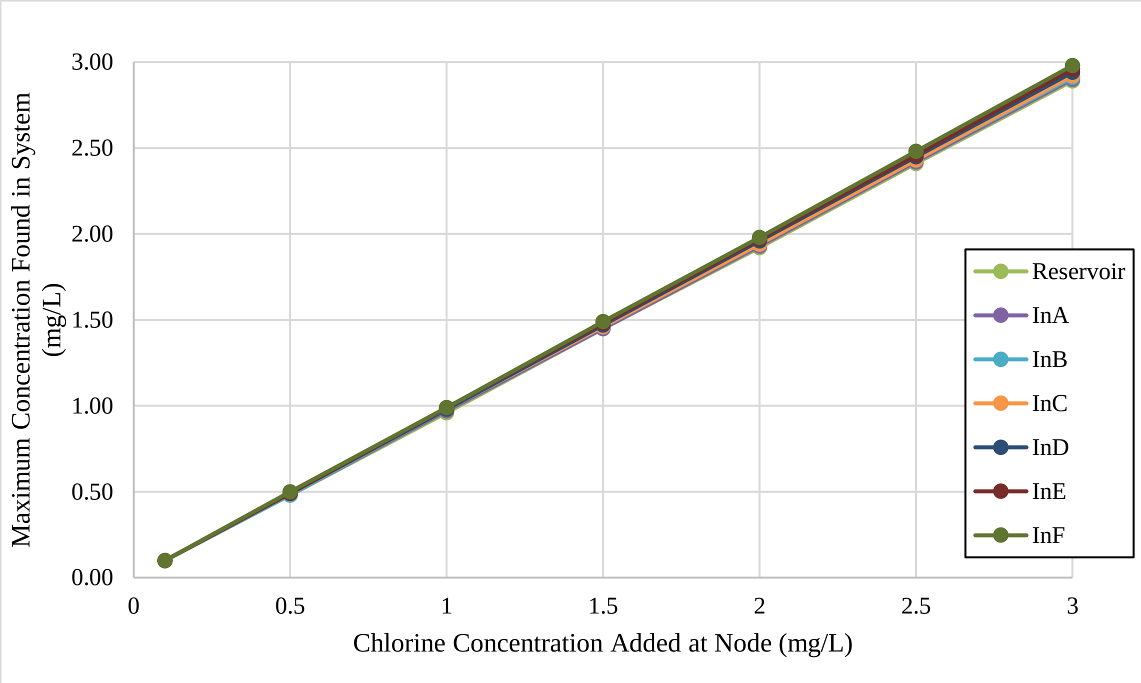

Figure 3-1. *Maximum chlorine residual in the Suyo water system after chlorination at different nodes.*

In all cases the maximum chlorine concentration was found at Node 1, the node closest to the points of chlorination. It was found to be nearly identical to the chlorination concentration. 3.5mg/L was deemed close to the maximum acceptable value of 4mg/L without exceeding it.

Table 3-4. *Percent of chlorine residual measurements throughout the Suyo water system at least 0.5 mg/L after stabilization when chlorination took place at the specified node.*

Chlorination (mg/L)	% Residual Measurements above 0.5 mg/L during Chlorination at Node						
	Reservoir	InA	InB	InC	InD	InE	InF
0.5	0%	0%	0%	0%	0%	0%	6%
1	99%	100%	100%	100%	100%	100%	100%
1.5	100%	100%	100%	100%	100%	100%	100%
2	100%	100%	100%	100%	100%	100%	100%
2.5	100%	100%	100%	100%	100%	100%	100%
3	100%	100%	100%	100%	100%	100%	100%

Location of chlorination also had very little effect on percent measurements of chlorine residual which met the Peruvian national standards. As can be seen in Tables 3.4 and 3.5 below, for all conditions modeled chlorination of 1.0 mg/L achieved the required minimum free chlorine concentrations at all nodes after stabilization.

Table 3-5. *Percent of chlorine residual measurements throughout the Suyo water system of at least 0.3 mg/L after stabilization when chlorination took place at the specified node.*

Chlorination (mg/L)	**% Residual Measurements above 0.3 mg/L during Chlorination at Node**						
	Reservoir	**InA**	**InB**	**InC**	**InD**	**InE**	**InF**
0.5	99%	99%	99%	99%	99%	99%	99%
1	100%	100%	100%	100%	100%	100%	100%
1.5	100%	100%	100%	100%	100%	100%	100%
2	100%	100%	100%	100%	100%	100%	100%
2.5	100%	100%	100%	100%	100%	100%	100%
3	100%	100%	100%	100%	100%	100%	100%

As was the case in the baseline model, attaining a minimum Ct value for 3-log giardia removal was found to be the most limiting condition. Tables 3-6 through 3-12 show the minimum Ct value achieved after stabilization at the nodes studied under different chlorination conditions. The required minimum Ct is included in the table. Nodes which do not achieve it have been highlighted.

Table 3-6. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at the reservoir.*

	Chlorination (mg/L)	**Minimum Ct Value at Node after Stabilization (min*mg/L)**									***Min Ct Required (min* mg/L)***
		Scho	**N76**	**N68**	**N52**	**N43**	**N34**	**N1**	**N2**	**N15**	
Chlorination at Reservoir	**0.5**	65	113	59	70	51	61	26	29	47	*149*
	1	130	225	116	140	102	124	52	57	93	*158*
	1.5	196	341	175	207	153	185	79	86	138	*168*
	2	261	456	234	279	203	248	105	114	186	*174*
	2.5	*325*	*566*	293	349	255	309	*131*	*142*	*232*	*182*
	3	390	682	*350*	*420*	*305*	*372*	158	171	278	*190*
	3.5	456	794	*409*	*490*	*356*	*433*	184	200	326	*197*

Table 3-7. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at node InA.*

	Chlorination (mg/L)	Minimum Ct Value at Node after Stabilization (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	N76	N68	N52	N43	N34	N1	N2	N15	
Chlorination at InA	0.5	63	111	59	68	48	61	24	26	45	*149*
	1	127	224	115	136	98	123	48	52	88	*158*
	1.5	189	335	172	206	147	185	72	79	134	*168*
	2	253	448	229	272	195	245	96	105	178	*174*
	2.5	316	559	284	340	244	306	120	131	222	*182*
	3	379	672	340	408	293	367	144	158	265	*190*

Table 3-8. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at node InB.*

	Chlorination (mg/L)	Minimum Ct Value at Node after Stabilization (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	N76	N68	N52	N43	N34	N1	N2	N15	
Chlorination at InB	0.5	61	108	54	66	47	58	21	24	42	*149*
	1	122	220	108	131	93	116	43	47	84	*158*
	1.5	183	328	162	198	139	174	*65*	71	126	*168*
	2	244	442	216	264	186	231	86	*95*	*168*	*174*
	2.5	*305*	*550*	270	330	232	289	107	119	209	*182*
	3	365	659	325	395	*279*	*347*	129	143	251	*190*

Table 3-9. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at node InC.*

	Chlorination (mg/L)	Minimum Ct Value at Node after Stabilization (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	N76	N68	N52	N43	N34	N1	N2	N15	
Chlorination at InC	0.5	59	107	52	63	45	56	19	21	40	*149*
	1	117	216	104	128	89	112	38	43	80	*158*
	1.5	177	325	157	193	134	167	58	64	120	*168*
	2	236	434	209	255	177	223	*77*	*86*	160	*174*
	2.5	*294*	*543*	261	319	222	279	96	108	*200*	*182*
	3	353	650	312	384	*266*	*335*	116	129	239	*190*

Table 3-10. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at node InD.*

	Chlorination (mg/L)	Minimum Ct Value at Node after Stabilization (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	N76	N68	N52	N43	N34	N1	N2	N15	
Chlorination at InD	0.5	53	102	48	60	39	38	15	17	35	*149*
	1	107	209	95	119	78	77	29	34	71	*158*
	1.5	160	313	144	178	118	116	*44*	51	106	*168*
	2	213	420	191	236	157	154	59	*68*	*141*	*174*
	2.5	*266*	*524*	239	295	196	193	73	85	177	*182*
	3	320	628	286	355	*236*	*231*	88	102	212	*190*

Table 3-11. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at node InE.*

	Chlorination (mg/L)	Minimum Ct Value at Node after Stabilization (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	N76	N68	N52	N43	N34	N1	N2	N15	
Chlorination at InE	0.5	47	99	43	54	29	45	10	12	31	*149*
	1	95	201	84	108	57	89	20	24	60	*158*
	1.5	142	303	127	161	86	133	29	36	92	*168*
	2	190	400	169	216	114	177	39	48	121	*174*
	2.5	237	504	212	270	*143*	222	49	61	152	*182*
	3	284	603	254	325	172	*266*	*59*	*73*	183	*190*

Table 3-12. *Minimum Ct at node specified after stabilization from different concentrations of chlorination added at node InF.*

	Chlorination (mg/L)	Minimum Ct Value at Node after Stabilization (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	N76	N68	N52	N43	N34	N1	N2	N15	
Chlorination at InF	0.5	42	93	31	49	18	38	5	7	22	*149*
	1	83	189	62	99	36	76	10	15	44	*158*
	1.5	124	285	94	148	55	113	15	22	67	*170*
	2	166	376	125	196	73	151	20	30	88	*179*
	2.5	208	472	156	245	91	188	25	37	111	*186*
	3	249	565	186	295	110	226	30	45	133	*194*

The closer to the town that chlorine was injected, the lower the Ct values achieved throughout the system. Indeed, with the original pipe diameter none of the chlorination strategies modeled were able to deliver 3-log giardia inactivation to the entire town.

3.3 Chlorination at Multiple Locations

Models were run to simulate chlorination of 0.5 mg/L at the reservoir as well as secondary chlorination at one of three nodes between the reservoir and the town. Figure 3-2 shows that, as before, the node of additional chlorination made minimal difference to the maximum chlorine residual found in the system.

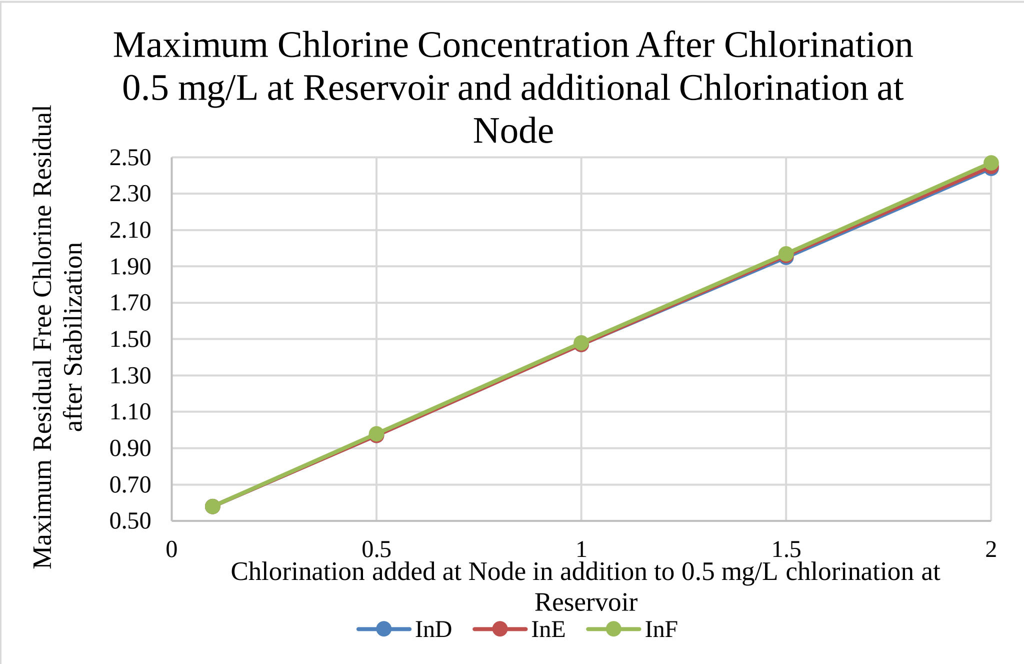

Figure 3-2. *Maximum chlorine residual in the Suyo water system after chlorination of 0.5 mg/L at the reservoir and additional chlorination at different nodes*

All secondary chlorination above 0.5 mg/L achieved minimum Peruvian water quality standards for residual chlorine measurements (Tables 3-14 and 3-15).

Table 3-13. *Percent of chlorine residual measurements at least 0.5 mg/L after stabilization from 0.5 mg/L chlorination at reservoir and additional chlorination at nodes InD, InE, and InF.*

Secondary Chlorination (mg/L)	% Residual Measurements above 0.5 mg/L during Chlorination at Reservoir and Node		
	InD	InE	InF
0.5	75%	76%	86%
1	100%	100%	100%
1.5	100%	100%	100%
2	100%	100%	100%

Table 3-14. *Percent of chlorine residual measurements at least 0.3 mg/L after stabilization from 0.5 mg/L chlorination at reservoir and additional chlorination at node InD, InE, and* InF.

Secondary Chlorination (mg/L)	% Residual Measurements above 0.3 mg/L during Chlorination at Reservoir and Node		
	InD	InE	InF
0.5	100%	100%	100%
1	100%	100%	100%
1.5	100%	100%	100%
2	100%	100%	100%

As with chlorination at only a single node, however, none of the permutations of two-node chlorination achieved minimum required Ct for 3-log giardia inactivation. Again, 4-log virus inactivation was achieved (Tables 3-15 through 3-17).

Table 3-15. *Minimum Ct at node specified after stabilization from 0.5 mg/L chlorination at the reservoir and different concentrations of chlorination added at node InD.*

	Chlorine (mg/L)	Minimum Ct Value at Node (after 10a) (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	76	68	52	43	34	1	2	15	
0.5 at Res + Flow Booster at InD	0.1	75	133	68	82	59	72	29	32	54	*149*
	0.5	118	219	106	130	90	113	41	46	82	*158*
	1	171	321	154	188	129	163	55	62	117	*168*
	1.5	225	428	201	248	169	214	70	79	152	*174*
	2	278	532	250	307	208	265	85	96	187	*182*

Table 3-16. *Minimum Ct at node specified after stabilization from 0.5 mg/L chlorination at the reservoir and different concentrations of chlorination added at node InE.*

	Chlorine (mg/L)	Minimum Ct Value at Node (after 10a) (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	76	68	52	43	34	1	2	15	
0.5 at Res + Flow Booster at InE	0.1	74	134	67	81	58	71	28	31	53	149
	0.5	113	214	102	124	85	107	36	41	77	158
	1	160	316	145	178	117	151	46	53	108	168
	1.5	207	415	188	232	150	197	56	65	138	174
	2	255	517	230	285	184	241	65	77	169	182

Table 3-17. *Minimum Ct at node specified after stabilization from 0.5 mg/L chlorination at the reservoir and different concentrations of chlorination added at node InF.*

	Chlorine (mg/L)	Minimum Ct Value at Node (after 10a) (min*mg/L)									*Min Ct Required (min*mg/L)*
		Scho	76	68	52	43	34	1	2	15	
0.5 at Res + Flow Booster at InF	0.1	74	133	66	80	57	70	27	30	52	149
	0.5	107	209	97	120	78	101	31	36	73	158
	1	148	306	134	169	103	139	36	43	98	168
	1.5	189	401	170	218	128	177	41	51	121	179
	2	231	500	207	267	152	215	47	58	143	182

3.4 Chlorination with Larger Pipe

Models were run to simulate chlorination at the reservoir with larger pipe diameters between the reservoir and Node 3 to increase chlorine contact time and therefore increase the Ct value. Velocity is less in a larger pipe since V=Q/A where V is velocity, Q is discharge, and A is the pipe cross-sectional area. Simulations were run for pipe diameters of 5", 6", 7", and 8". Pipe diameter was found to make a small difference to maximum chlorine residual with smaller diameter pipes delivering higher concentrations of free chlorine as showing in Figure 3-3.

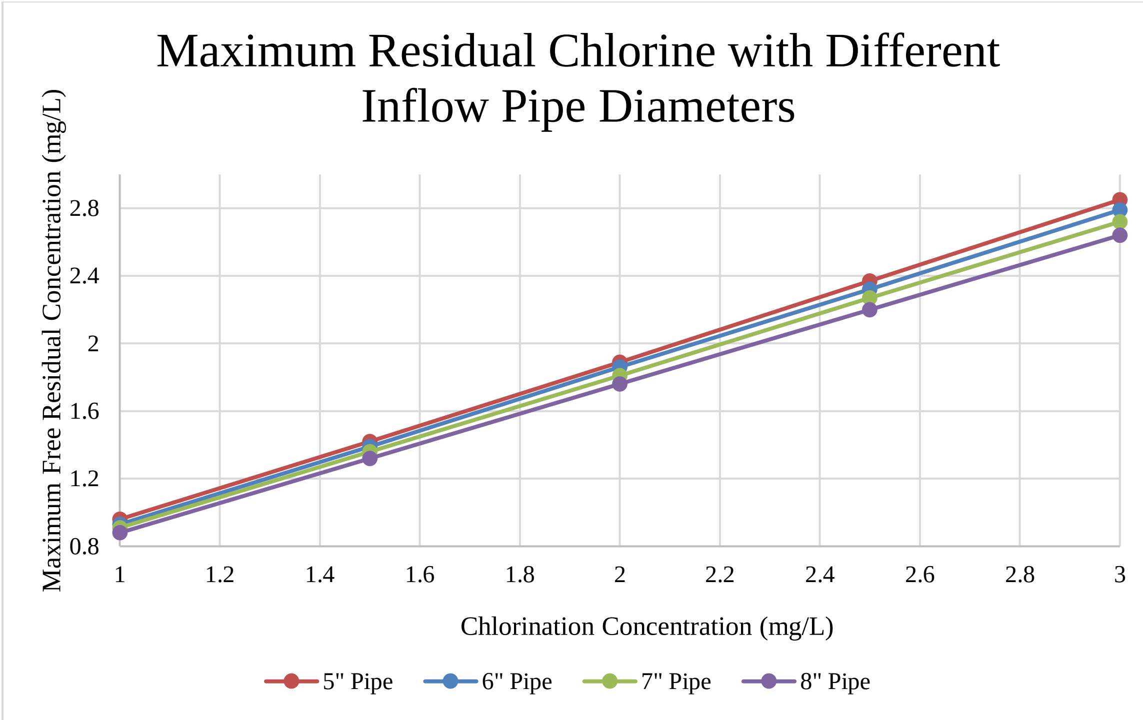

Figure 3-3. *Maximum Chlorine Residual found in the Suyo Water System after Chlorination at the reservoir with different inflow pipe diameters.*

For chlorination concentrations of 1.0 mg/L and above all studied pipe diameters delivered high enough residual chlorine throughout the water system to be consistent with Peruvian regulations (Tables 3-18 and 3-19).

Table 3-18. *Percent of chlorine residual measurements at least 0.5 mg/L after stabilization from chlorination at the reservoir with different pipe sizes.*

Chlorine	**% Residual Measurements above 0.5 mg/L after Chlorination with Pipe Diameter**			
(mg/L)	**5"**	**6"**	**7"**	**8"**
1	100%	100%	100%	99%
1.5	100%	100%	100%	100%
2	100%	100%	100%	100%
2.5	100%	100%	100%	100%
3	100%	100%	100%	100%

All modeled pipe sizes can achieve 3-log giardia inactivation throughout the water system with a chlorination concentration of 3 mg/L or lower (Tables 3-20 through 3-23). Larger pipes deliver consistently higher Ct values and can, therefore, achieve 3-log giardia inactivation at lower chlorine concentrations.

Table 3-19. *Percent of chlorine residual measurements at least 0.3 mg/L after stabilization from chlorination at the reservoir with different pipe sizes.*

Chlorination	**% Residual Measurements above 0.3 mg/L after Chlorination with Pipe Diameter**			
(mg/L)	5"	6"	7"	8"
1	100%	100%	100%	100%
1.5	100%	100%	100%	100%
2	100%	100%	100%	100%
2.5	100%	100%	100%	100%
3	100%	100%	100%	100%

Table 3-20. *Minimum Ct at node specified after stabilization from chlorination at the reservoir with a 5" pipe diameter.*

			Minimum Ct at Node after Stabilization (min*mg/L)									**Min Ct Required (min*mg/L)**
			1	**2**	**15**	**43**	**34**	**Scho**	**52**	**68**	**76**	
5" Pipe	**Chlorine added at Reservoir**	**1**	73	78	111	121	143	151	155	140	244	158
		1.5	110	118	167	182	212	226	237	210	372	168
		2	146	156	224	241	284	302	315	279	491	174
		2.5	183	195	279	302	355	377	394	349	616	179
		3	220	234	335	362	426	453	472	420	741	186

Table 3-21. *Minimum Ct at node specified after stabilization from chlorination at the reservoir with a 6" pipe diameter.*

			Minimum Ct at Node after stabilization (min*mg/L)									**Min Ct Required (min*mg/L)**
			1	**2**	**15**	**43**	**34**	**Scho**	**52**	**68**	**76**	
6" Pipe	**Chlorine added at Reservoir (mg/L)**	**1**	98	101	137	143	164	175	183	162	270	162
		1.5	146	153	206	215	246	261	273	243	404	170
		2	195	204	274	287	328	350	363	324	540	179
		2.5	244	255	341	359	411	436	454	405	674	190
		3	293	305	411	431	493	523	544	486	807	197

Table 3-22. *Minimum Ct at node specified after stabilization from chlorination at the reservoir with a 7" pipe diameter.*

			Minimum Ct at Node after stabilization (min*mg/L)									Min Ct Required (min*mg/L)
			1	**2**	**15**	**43**	**34**	**Scho**	**52**	**68**	**76**	
7" Pipe	**Chlorine added at Reservoir (mg/L)**	**1**	126	131	163	169	194	199	211	192	290	162
		1.5	188	198	245	255	288	300	321	286	436	170
		2	251	264	324	340	385	398	427	382	579	179
		2.5	315	330	408	424	482	498	532	478	722	190
		3	377	395	489	509	578	597	639	574	869	197

Table 3-23. *Minimum Ct at node specified after stabilization from chlorination at the reservoir with an 8" pipe diameter.*

			Minimum Ct at Node after stabilization (min*mg/L)									Min Ct Required (min*mg/L)
			1	**2**	**15**	**43**	**34**	**Scho**	**52**	**68**	**76**	
8" Pipe	**Chlorine added at Reservoir (mg/L)**	**1**	161	167	200	205	223	230	248	221	313	158
		1.5	241	250	302	310	333	345	371	332	470	170
		2	321	334	399	413	445	461	497	441	626	179
		2.5	401	415	502	515	558	578	619	553	786	186
		3	482	499	601	618	668	694	742	662	942	194

4 Conclusions and Recommendations

The Suyo water system is currently delivering water which achieves Peruvian legal standards of water quality, 4-log inactivation of viruses, and is well below EPA and WHO standards of safe free chlorine concentration. It does not, however, achieve 3-log giardia inactivation. An effective method of upgrading the current system such that 3-log inactivation is achieved would be to replace the pipe between the reservoir and the town to 8" in diameter. This would increase the ability of the chlorine to interact with the water, raising Ct values to within required levels.

Increasing the concentration of chlorination was found to provide 3-log inactivation of giardia to a larger percentage of the town but did not provide full coverage for all users.

No benefit was found in moving the point of chlorination closer to the city nor in chlorinating both at the reservoir and at an additional node. Doing so made minimal impact on maximum chlorine residual concentrations while reducing the amount of time the chlorine had to disinfect the water, thereby reducing the Ct.

5 Discussion

This study identified time as the main limiting factor of effectiveness of chlorination. It was found that lower concentrations of chlorination could be equally effective or more effective than higher concentrations as long as there was more time for the chlorine disinfect the water. The only method studied was to increase the diameter of the pipe between the reservoir and the town, however, other methods may be equally productive such as increasing the size of the reservoir to increase tank residence time.

It is also important to note that although increasing the pipe diameter improved effectiveness of chlorination, the benefit of physically replacing the pipe, at least in this instance, did not outweigh the cost. At the time of the study,the Suyo system met Peruvian legal requirements for a water system. Current chlorination practices provide sufficient protection against viruses and Giardia, used as the main indicator for Ct value, had not been an issue. When the pipe needs to be replaced due to maintenance it may be beneficial to replace it with a wider diameter but to do so before hand would be an unnecessary expense to the community.

The EPANET model itself could be improved by using field data of on-site chlorine residuals to determine more accurate coefficients to model bulk and wall reactions for chlorine decay.

It must also be kept in mind that Suyo utilizes ground water. Towns which rely on surface water will need to pay more attention to organic materials which may react with chlorine, potentially creating harmful byproducts or at least reducing the effectiveness of the chlorination.

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Figure 1.1: A map of Peru with the district of Suyo labeled. This figure comes from Google Maps and is fair use for research papers. Accessed April 2018.

B Ct Tables

The following tables are US EPA Ct values in min*mg/L for the inactivation of Giardia Cysts and viruses by free chlorine published by Clean Water Systems in 2007.

Table B-1 *Ct values for 3-log (99.9%) inactivation of Giardia cysts by free chlorine at water temperature 10.0 °C (50 °F)*

Free Residual (mg/L)	pH						
	≤ 6.0	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**	**≤ 9.0**
≤ 0.4	73	88	104	125	149	177	209
0.6	75	90	107	128	153	183	218
0.8	78	92	110	131	158	189	226
1.0	79	94	112	134	162	195	234
1.2	80	95	114	137	168	200	240
1.4	82	98	116	140	170	206	247
1.6	83	99	119	144	174	211	253
1.8	88	101	122	147	179	215	259
2.0	87	104	124	150	182	221	265
2.2	89	105	127	153	186	225	271
2.4	90	107	129	157	190	230	276
2.6	92	110	131	160	194	234	281
2.8	93	111	134	163	197	239	287
3.0	95	113	137	166	201	243	292

Table B-2 *Ct values for inactivation of viruses by free chlorine*

Temperature (°C)	Log Inactivation					
	2.0-log		**3.0-log**		**4.0-log**	
	pH 6-9	**pH 10**	**pH 6-9**	**pH 10**	**pH 6-9**	**pH 10**
0.5	6	45	9	66	12	90
5	4	30	6	44	8	60
10	3	22	4	33	6	45
15	2	15	3	22	4	30
20	1	11	2	16	3	22
25	1	7	1	11	2	15

C EPANET Model Data

For the EPANET model, the pipes within the city are labeled after the streets they run under. For example, the segments of pipe which run under Avenida Amazonas are labeled “AMAZ1”, “AMAZ2”, etcetera. The segments of pipe leading from the reservoir to the town are simply labeled “Pipe 1”, “Pipe 2”, and so on. Information used to model it appears in Tables C-1.

Table C-1 *EPANET model network pipes*

Pipe ID	Length (ft)	Diameter (in)	Roughness	Bulk Coeff.	Wall Coeff.	Connected Nodes
Ama1	421	1	100	-1	0	16,15
Amaz2	93	1	100	-1	0	17,16
Amaz3	92	2	100	-1	0	17,18
Amaz4	110	2	100	-1	0	19,18
Amaz5	71	2	100	-1	0	20,19
Amaz6	66	2	100	-1	0	20,21
Amaz7	146	2	100	-1	0	22,21
Avelar	209	4	100	-1	0	1,2
Bol1	138	4	100	-1	0	2,3
Bol10	198	1	100	-1	0	66,67
Bol2	118	4	100	-1	0	3,12
Bol3	124	4	100	-1	0	12,19
Bol4	134	2	100	-1	0	19,24
Bol5	75	2	100	-1	0	24,26
Bol6	127	2	100	-1	0	26,30
Bol7	108	2	100	-1	0	30,45
Bol8	48	2	100	-1	0	45,56
Bol9	126	2	100	-1	0	56,57
Cem1	173	2	100	-1	0	4,3
Cem2	49	1	100	-1	0	5,3
Cem3	276	1	100	-1	0	6,5
Cem4	183	1	100	-1	0	6,7
CemTankLine	1	2	100	-1	0	4, CemTank
Escalera	468	2	100	-1	0	34,school
Grau1	125	1	100	-1	0	48,49
Grau2	97	1	100	-1	0	48,50
Grau3	133	1	100	-1	0	50,51
Grau4	127	1	100	-1	0	51,52

Guep1	141	2	100	-1	0	35,34
Guep10	41	1	100	-1	0	47,48
Guep2	182	2	100	-1	0	37,35
Guep3	183	2	100	-1	0	39,37
Guep4	63	2	100	-1	0	42,39
Guep5	110	2	100	-1	0	42,43
Guep6	106	2	100	-1	0	44,43
Guep7	99	2	100	-1	0	45,44
Guep8	149	2	100	-1	0	45,46
Guep9	152	2	100	-1	0	47,46
Iquit1	268	1	100	-1	0	40,39
Iquit2	188	1	100	-1	0	41,39
JRMV1	106	1.5	100	-1	0	28,32
JRMV2	135	1.5	100	-1	0	32,47
JRMV3	73	1.5	100	-1	0	47,60
JRMV4	269	1.5	100	-1	0	60,71
JRMV5	197	1	100	-1	0	71,72
Leti	127	2	100	-1	0	14, 21
Leti1	99	2	100	-1	0	25,21
Leti10	153	2	100	-1	0	73,74
Leti11	131	2	100	-1	0	74,75
Leti12	542	1	100	-1	0	75,76
Leti2	82	2	100	-1	0	25,27
Leti3	124	1	100	-1	0	31,46
Leti4	87	2	100	-1	0	46,59
Leti5	86	2	100	-1	0	59,58
Leti6	59	2	100	-1	0	58,69
Leti7	87	2	100	-1	0	69,68
Leti8	284	2	100	-1	0	68,70
Leti9	301	2	100	-1	0	70,73
Lima1	151	2	100	-1	0	26,27
Lima2	140	2	100	-1	0	27,28
Lima3	247	2	100	-1	0	22,28
Lima4	112	1	100	-1	0	7,9
Lima5	192	1	100	-1	0	7,8
Mara1	303	1	100	-1	0	37,38
Mara2	123	1	100	-1	0	35,36
Mara3	315	1	100	-1	0	36,64
Mara4	433	1	100	-1	0	64,65
NoNem	158	1	100	-1	0	35,33

Ojeda1	175	1	100	-1	0	62 to 66
Ojeda2	146	1	100	-1	0	66 to 68
Ojeda3	116	2	100	-1	0	71,68
Pipe 1	1	4	100	-1	0	Res,InA
Pipe 2	1	4	100	-1	0	InA,InB
Pipe 3	1	4	100	-1	0	InB,InC
Pipe 4	1164	4	100	-1	0	InC,InD
Pipe 5	1164	4	100	-1	0	InD,InE
Pipe 6	1164	4	100	-1	0	InE,InF
Pipe 7	1164	4	100	-1	0	InF,1
Piura1	196	1	100	-1	0	11,10
Piura2	141	1	100	-1	0	12,11
Piura3	96	2	100	-1	0	12,13
Piura4	40	2	100	-1	0	13,14
Prado1	124	1	100	-1	0	54,41
Prado2	103	2	100	-1	0	55,54
Prado3	102	2	100	-1	0	57,55
Prado4	157	2	100	-1	0	58,57
Ugart1	155	1	100	-1	0	17,23
Ugart2	221	1	100	-1	0	23,29
Ugart3	106	1	100	-1	0	43,29
Ugart4	112	1	100	-1	0	43,53
Ugart5	72	1	100	-1	0	53,54
Ugart6	105	1	100	-1	0	54,61
Ugart7	53	1	100	-1	0	61,62
Ugart8	211	1	100	-1	0	62,63

Apart from the school, the reservoir, and the water tank in the cemetery the labels generated automatically by EPANET were kept as labels for the nodes. The data used to model them appears in Table C-2.

Table C-2 *EPANET model network nodes*

Node ID	Elevation (ft)	Base Demand (GPM)	Initial Quality (hrs)
Junc 1	1414	0	0
Junc 2	1414	1.4	0
Junc 3	1414	0	0
Junc 4	1420	0.38	0

Junc 5	1400	0.38	0
Junc 6	1390	1.53	0
Junc 7	1390	0	0
Junc 8	1380	0.64	0
Junc 9	1385	0.64	0
Junc 10	1394	0.38	0
Junc 11	1394	1.53	0
Junc 12	1394	0	0
Junc 13	1394	0.51	0
Junc 14	1394	0.13	0
Junc 19	1384	0	0
Junc 18	1381	0.89	0
Junc 17	1381	0	0
Junc 16	1381	0.83	0
Junc 15	1381	1.14	0
Junc 20	1390	0.38	0
Junc 21	1390	0	0
Junc 22	1393	0.68	0
Junc 23	1376	0.51	0
Junc 24	1381	1.27	0
Junc 25	1366	1.14	0
Junc 26	1374	0	0
Junc 27	1342	0.26	0
Junc 28	1352	0.13	0
Junc 29	1371	0.26	0
Junc 30	1369	0.76	0
Junc 45	1361	0	0
Junc 43	1371	0	0
Junc 44	1366	1.27	0
Junc 42	1371	4.55	0
Junc 39	1371	0	0
Junc 37	1359	0	0
Junc 35	1359	0	0
Junc 34	1359	1.02	0
Junc Scho	1400	4.59	0
Junc 46	1361	0	0
Junc 31	1352	1.02	0
Junc 32	1369	0.76	0
Junc 47	1356	0	0
Junc 48	1346	0	0

Junc 49	1346	0.51	0
Junc 50	1346	1.28	0
Junc 51	1346	0.14	0
Junc 52	1346	0.13	0
Junc 56	1366	0.13	0
Junc 57	1366	0	0
Junc 59	1361	0.76	0
Junc 58	1361	0	0
Junc 55	1371	0.51	0
Junc 54	1381	0	0
Junc 53	1376	0.51	0
Junc 41	1391	1.4	0
Junc 40	1371	1.53	0
Junc 61	1381	0.26	0
Junc 62	1385	0	0
Junc 63	1389	0.76	0
Junc 69	1361	0.34	0
Junc 68	1361	0	0
Junc 70	1361	1.78	0
Junc 66	1371	0	0
Junc 67	1373	1.78	0
Junc 60	1359	0.55	0
Junc 71	1361	0	0
Junc 72	1361	0.72	0
Junc 73	1361	0.64	0
Junc 74	1361	0.89	0
Junc 75	1361	0.13	0
Junc 76	1361	0.26	0
Junc 38	1331	0.89	0
Junc 33	1331	0.77	0
Junc 36	1331	0.51	0
Junc 64	1336	0	0
Junc 65	1336	0.26	0
Junc InC	1490	0	0
Junc InB	1490	0	0
Junc InA	1490	0	0
Junc InD	1472.85	0	0
Junc InE	1453.3	0	0
Junc InF	1433.75	0	0
Resvr RES	1493	#N/A	0

Tank CemTank	1420	#N/A	0

There was one tank in Suyo. It was an open air tank in the cemetery. Information used for modeling it is in Table C-3.

Table C-3 *EPANET model tank*

Cemetary Tank	
Label	CemTank
Elevation	1420
Initial Level (ft)	4
Minimum Level (ft)	0
Maximum Level (ft)	4.5
Diameter (ft)	3.9

Table C-4 *EPANET model demand pattern*

Hour	Demand Pattern
1	0.5
2	0.2
3	0
4	0
5	0.2
6	0.5
7	1.5
8	1.5
9	1.5
10	1
11	1
12	1
13	1.5
14	1.5
15	1.5
16	1
17	1
18	1
19	1.5
20	1.5

21	1.5
22	1
23	1
24	1