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Effectiveness of In-Line Chlorination of Gravity Flow Water Supply in Two Rural Communities in Panama

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Effectiveness of In-Line Chlorination of Gravity Flow Water Supply in Two Rural Communities in Panama

by

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Abstract

It is well established that water quality is directly linked to health. In-line chlorination is one technology that can be used in the developing world to potentially inactivate pathogens and improve water quality. The purpose of this study was to determine the effectiveness of the Panamanian Ministry of Health's in-line PVC chlorinator under three different operating conditions in a rural water supply system. Free and total chlorine were measured entering the storage tank, leaving the storage tank, and at three households along the transmission line of the water system in the two rural indigenous communities of Calabazal and Quebrada Mina in western Panama during April-August 2011. The Ct method for disinfection was used to compare the measured free chlorine concentration to the concentration required to inactivate common pathogens found in gravity flow water systems in Panama, such as *E. coli*, *Salmonella typhi*, Hepatitis A, *Giardia lamblia*, and *E. histolytica,* as well as other pathogens of interest to the global health community, such as *Vibrio cholerae* and Rotavirus. When the chlorine tablet was sealed in a plastic wrapper prior to use to prevent contact with humid surroundings, the chlorine was able to dissolve in seven days instead of three hours into the transmission line. The use of one tablet, sealed in a plastic wrapper before use, was able to obtain the required free chlorine concentration estimated to disinfect *E. coli*, *Vibrio cholerae*, Rotavirus, *Salmonella typhi*, and Hepatitis A. However, it did not achieve a free chlorine concentration above 0.27 mg/L

needed to inactivate *Giardia lamblia* nor above 0.35 mg/L needed to inactivate *E. histolytica*. The use of three properly stored tablets in the chlorinator was able to provide a free chlorine concentration above 0.35 mg/L for only one day, reaching 0.37 mg/L, before falling below 0.35 mg/L to a level of 0.26 mg/L the next day. The study suggests that with three tablets the in-line PVC chlorinator can be an effective technology if slightly more free chlorine concentration can enter the system. The cost of this technology could be allocated to every owner with a house connection in the communities of Calabazal and Quebrada Mina by increasing their monthly tariff by $1 each month.

Chapter 1: Introduction

It has been extensively noted in many peer reviewed reports that water quality is directly linked to health (e.g., Semenza et al., 1998, Egorov et al., 2002). International organizations like the World Health Organization (WHO), United Nations (UN), World Bank, and United States Agency for International Development (USAID) all devote extensive time, money and energy into water management, supply and quality. The Millennium Development Goals state that by 2015, the proportion of the population without sustainable access to drinking water and basic sanitation should be halved compared to 1990 baselines, noting that accelerated and targeted efforts are needed especially in rural households.

Panama, with a population of around 3.5 million, borders Costa Rica and Columbia, as shown in Figure 1 (CIA World Factbook, 2011). Panama's Cordillera mountain range bisects the Caribbean coast from the Pacific coast. The Comarca Ngabe Bugle, situated in western Panama, is home to about 150,000 inhabitants, the majority of Panama's indigenous population (Instituto Nacional, 2011). 83% of indigenous people live below the poverty line, 70% in extreme poverty, compared to 33% of non-indigenous below the poverty line and 13% in extreme poverty.

Figure 1: Geographical Location of Panama
(CIA World Factbook, 2011)

According to the WHO/UNICEF (United Nations Children's Fund) Joint Monitoring Program for water and sanitation, 97% and 83% of Panama's urban and rural population respectively receive water from an improved source (WHO/UNICEF, 2011). In the Comarca Ngabe Bugle area of Panama only 23% of the population receives piped water (World Bank, 2000). Gastrointestinal diseases like *Salmonella typhi*, Hepatitis A, and amebiasis are reported to be most common in Panama (PAHO, 2007). The Gorgas Institute found that in the town of San Felix, three miles away from the focus of this thesis, 67% of the 379 children under 12 years old tested positive for intestinal parasites. Specific causal agents are noted below in Table 1. This study will only focus on pathogens primarily transmitted by water, not soil.

Table 1: Intestinal Parasites in Children Under 12 Years Old during Testing in San Felix compared with Testing Throughout Panama and their Primary Method of Transmission (Adapted from Gorgas Institute, 2011)

Causal Agent	**San Félix (n=379)**	**Panama (n=2 026)**	**Primarily Transmitted by Water or Soil**
Giardia lamblia	35 (9.2%)	314 (15.5%)	Water
E. coli	44 (12%)	129(6.4%)	Water
Hystolitica	14 (3.7%)	82 (4.0%)	Water
I. buschii	29 (7.6%)	63(3.1%)	Water
C. mesnilii	3(0.8%)	14 (0.7%)	Water
Crypstoridium spp.	5(1.3%)	87 (4.3%)	Water
C. cayetanesis	5 (1.3%)	7 (0.3%)	Water
C. belli	0 (0%)	1(0.05%)	Water
S. stercolaris	1(0.4%)	13 (0.64%)	Water and Soil
A.lumbricoides	69(18.2%)	189 (9.3%)	Soil
E. nana	15(3.9%)	74(3.6%)	Soil
Uncinarias	23(6.1%)	40 (1.9%)	Soil
T. trichura	10(2.6%)	26(1.3%)	Soil
E. vernicularise	0 (0%)	1 (0.05%)	Soil
H. nana	1(0.4%)	9(0.4%)	Soil
Total	**254 (67.0%)**	**1039(51.3%)**	

Although temperatures remain much the same throughout the year, Panama's great seasonal variation in precipitation complicates the water supply situation. Although precipitation data for the Comarca Ngabe Bugle was unavailable, data from Panama City in Table 2 indicates the general trend in Panama that the months of December-April are drier while May-November are much wetter.

Rural communities in the foothills of the Comarca take advantage of the short distance from the high mountains to the flat coast and often use gravity to capture spring water and transport via PVC pipes to their houses. Community members also hike to unprotected springs to obtain their water. During the periods of low rainfall, the months of December to April, many of these springs dry, making water access even more difficult.

Table 2: Panama Monthly Rainfall Based on Monthly Averages for the 30-year Period 1971-2000
(Reproduced from World Weather Information Service, 2011)

Month	Mean Temperature °F		Mean Total Rainfall (mm)	Mean Number of Rain Days *
	Daily Minimum	Daily Maximum		
Jan	65.3	92.1	29.3	2.9
Feb	65.1	93.6	10.1	1.3
Mar	65.1	94.6	13.1	1.4
Apr	67.1	95.7	64.7	4.9
May	70.0	94.1	225.1	15
Jun	70.3	92.8	235.0	16
Jul	69.8	93.0	168.5	14
Aug	69.6	93.0	219.9	15
Sep	69.8	91.2	253.9	17
Oct	69.4	90.7	330.7	20
Nov	68.5	91.2	252.3	16
Dec	66.6	91.9	104.6	7.5

Mean number of rain days = Mean number of days with at least 0.1 mm of rain.

Motivation, Objectives, and Hypotheses

Panama has to increase both urban and rural population access to improved water sources in order to meet its MDG commitments in 2015. With only 83% of the rural population having access to an improved water source and living in regions close to natural springs, the springs become the major water source. Water originating from these rural springs requires protection through the installation of a spring box and disinfection because of possible contamination due to the close proximity to fields and pasture. The dispersed nature of the communities and households that are served by a spring makes decentralized forms of disinfection the most feasible.

Methods of disinfection used in Panama include point of use treatment at the household level, drip chlorinators installed directly above a water storage tank, or in-line PVC chlorinators, which are modeled after the more expensive in-line chlorinators used for pools in other parts of the world. The in-line PVC chlorinators are a low-cost solution that the Panama Ministry of Environmental

Health promotes in the Comarca Ngabe Bugle. However, the author of this thesis found no scientific studies or reports on the effectiveness of these in-line chlorinators in estimated pathogen (any disease-causing agent) destruction via provision of sufficient chlorine and contact time in the storage and distribution system. EPA states that a residual amount of chlorine after water leaves the treatment tank/plant inactivates microorganisms in the distribution system, indicates distribution system upset and controls biofilm growth (EPA, 2011).

Accordingly, the motivation for this study is to determine whether in-line chlorination systems located in rural water supply systems effectively disinfect pathogens common to Panama and other parts of the world by examining the concentration and contact time of chlorine in rural water supply systems.

The study has the following two objectives:

1. Develop an understanding of the drinking water supply systems in two indigenous rural communities in Panama in order to determine if disinfection by in-line application of chlorine is effective in the disinfection of pathogens in gravity flow water systems.

2. Provide guidance on the proper concentration and contact time required to disinfect common pathogens identified in Panama and other parts of the world.

The study has four hypotheses.

1. There is greater chlorine concentration in the gravity-fed water system in the first two hours after a new chlorine tablet is added to an in-line chlorinator than after more time.

    Task: Measure chlorine concentration in the system within two hours using the Hach Colorimeter after a new tablet is added to an in-line chlorinator, than continue testing concentration to determine effect of time.

2. Home water connections nearest the chlorinator will have higher chlorine concentration than home water connections farther away.

    Task: Measure the chlorine concentration at home water connections located at various distance intervals from the chlorinator.

3. The chlorine tablet will dissolve in proportion to the flow entering the tank.

    Task: Measure weight loss of the chlorine tablet and measure the chlorine concentration during the rainy season and dry season.

4. The application of the chlorine tablet in the in-line chlorinator will result in free chlorine concentration necessary to achieve the Ct values required to disinfect specific pathogens that may be present in Panamanian gravity flow water supply distribution systems.

    Task: Obtain list of commonly occurring pathogens in Panama along with established Ct values for those pathogens. Compare the established Ct values with Ct values determined from field measurements of chlorine concentration and contact time.

Chapter 2: Literature Review

While no scientific studies were identified by the author directly related to monitoring in-line disinfection of rural water supply systems in the developing world, research in the developing world has been focused on the selection criteria of small scale gravity driven, water powered, and diffusion chlorinators in the developing world (Skinner, 2001) and the effectiveness and acceptance of household chlorination in the developing world. The closest study found was on the effectiveness of Pulsar 1 and Aquatab chlorinators in Northern Ghana (Cash-Fitzpatrick, 2008).

Background on Water Disinfection

The Ct approach relates C, the concentration of a chemical disinfectant (e.g., mg/L of a disinfectant such as free chlorine, ozone, or chlorine dioxide) with t, the residence time of the chemical disinfectant in the water system. The concentration of a particular disinfectant can be multiplied by time to produce a Ct value. Ct values vary depending on the type of disinfection agent, pathogen of interest, and water quality parameters such as pH and temperature. Current disinfection methods include using oxidizing agents like chloramines, free chlorine, combined chlorine, chlorine dioxide, or ozone or by using physical agents like UV light. Figure 2 portrays the Ct values at which five disinfectants are effective in inactivating common pathogens.

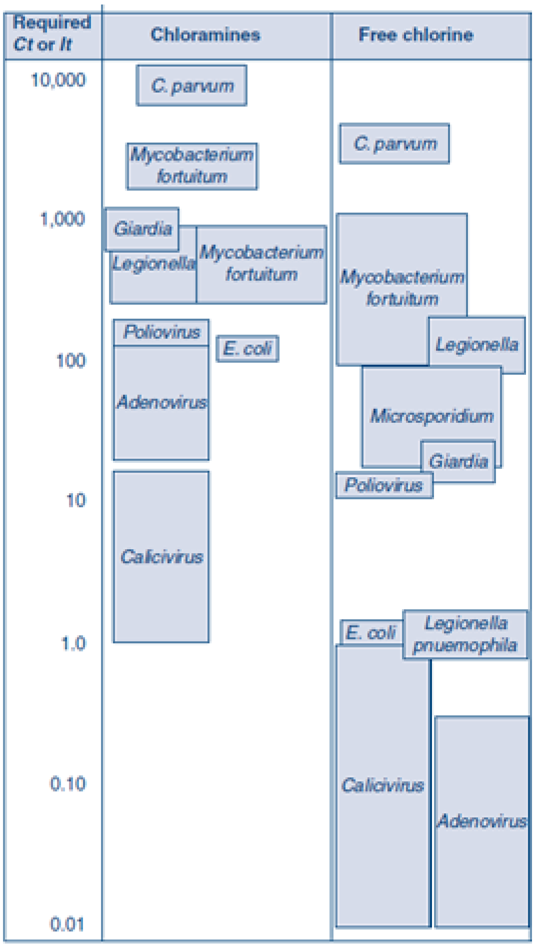

Figure 2: Overview of Ct Requirements of Common Disinfectant Agents in Pathogen Inactivation
(Adapted from Mihelcic and Zimmerman, 2010)

Chlorine, a common disinfectant, is an oxidizing agent that reacts with many substances, including iron, manganese, hydrogen sulfide, organic compounds, and ammonia. To ensure that the chlorine is disinfecting pathogens rather than solely reacting with the dissolved substances mentioned above, the chlorine dosage must always exceed the chlorine demand. Subtracting the demand from the dosage gives the chlorine concentration.

Free chlorine is measured by the quantity of hypochlorous acid (HOCl) and hypochlorite (OCl^-) ion present in an aqueous solution. The reaction involving adding calcium hypochlorite to water (type of chlorine present in the chlorine tablets used in this study) is shown as.

$$Ca(OCl)_2 + 2H_2O \rightarrow Ca^{2+} + 2HOCl + 2OH^-$$
$$HOCl \leftrightarrow H^+ + OCl^-$$

However, ammonia (NH_3), if present, reacts with hypochlorous acid (HOCl) to form the weak disinfectant chloramines, which contain between one (NH_2Cl) to three (NCl_3) moles of chlorine per mole of nitrogen.

$$NH_3 + HOCl \leftrightarrow NH_2Cl \text{ (monochloramine)} + H_2O$$
$$NH_2Cl + HOCl \leftrightarrow NHCl_2 \text{ (dichloramine)} + H_2O$$
$$NHCl_2 + HOCl \leftrightarrow NCl_3 \text{ (trichloramine)} + H_2O$$

The chloramines, referred to as combined chlorine, need longer contact times and higher concentrations than their free chlorine concentration counterparts. Adding free chlorine to combined chlorine results in the quantity of total chlorine.

If ammonia is not present, all the concentration is said to be free chlorine. When ammonia is present, the situation is different. Following Figure 3, once the chlorine has reacted with any other chemicals or materials present, the chlorine remaining is called the chlorine concentration, serving to disinfect the water. At this point the chlorine reacts with ammonia to form chloramine compounds. Free chlorine can only be formed after all ammonia has been converted.

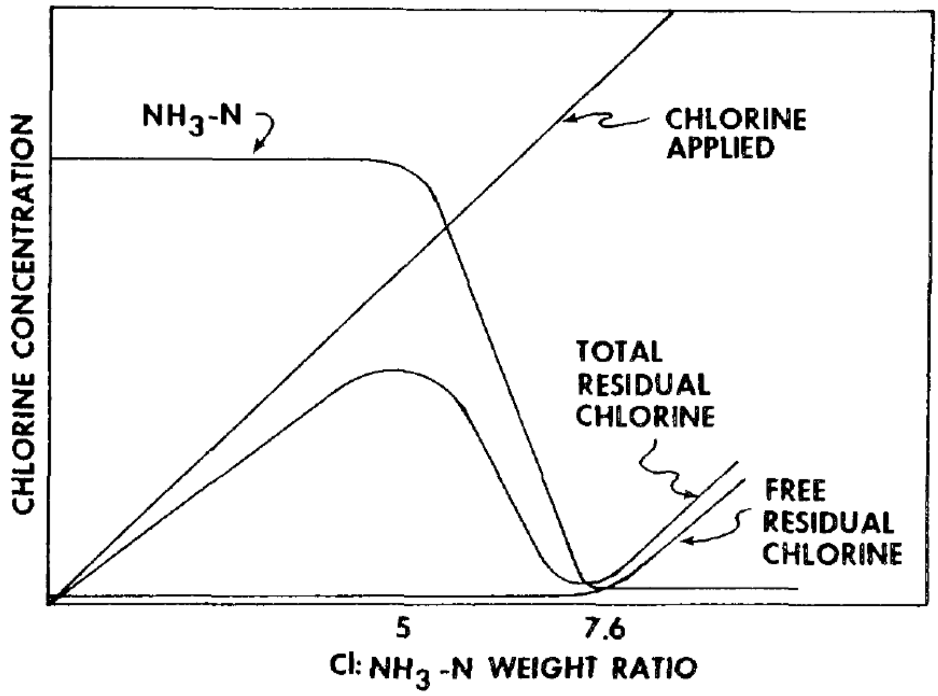

Figure 3: Typical Breakpoint Chlorination Curve based on Chlorine Applied and Chlorine Concentrations
(Reproduced from EPA, 1978)

A common way to describe the kinetics of the disinfection process is to use Chick's law, which assumes that a first-order equation can relate the concentration of chlorine and the number of organisms. The differential equation is $dN/dt = -K \times N$, where dN/dt is the rate of change in the number of organisms with time (organisms/volume/time), N is the concentration of organisms (organisms/volume), and K is the Chick's law rate constant (1/time).

The Focus on Disinfection

Pathogens are commonly present in drinking water around the world. Diarrheal diseases and other water-borne pathogens can cause significant negative health consequences, thus inactivation of these pathogens is pursued. One option is to protect and improve the water source, the other is to disinfect the water before it reaches the consumer.

Physical and Chemical Disinfection Strategies

If improving the water source is not preferred, the water can be disinfected. Options can be physical like water boiling, UV radiation, and filtration or chemical with the use of chlorine gas, chlorine solution, ozone gas, or iodine. Because chlorine is both simple and relatively inexpensive, it is often the preferred choice in the developing world. The World Health Organization reports that "chlorine residual throughout the distribution system is an essential safety measure when distribution system integrity cannot be assured," a common situation in the developing world (WHO, 2003). Table 3 reports that bacteria has low resistance to chlorine, moderate resistance to viruses and helminthes, and high resistance to most protozoa.

Table 3: Description of Health Significance, Persistence in Water Supplies, Resistance to Chlorine, Relative Infectivity, and Important Animal Source of Common Bacteria, Viruses, Protozoa, and Helminths

Pathogen	Health significance[b]	Persistence in water supplies[c]	Resistance to chlorine[d]	Relative infectivity[e]	Important animal source
Bacteria					
Burkholderia pseudomallei	High	May multiply	Low	Low	No
Campylobacter jejuni, C. coli	High	Moderate	Low	Moderate	Yes
Escherichia coli – Pathogenic[f]	High	Moderate	Low	Low	Yes
E. coli – Enterohaemorrhagic	High	Moderate	Low	High	Yes
Legionella spp.	High	May multiply	Low	Moderate	No
Non-tuberculous mycobacteria	Low	May multiply	High	Low	No
Pseudomonas aeruginosa[g]	Moderate	May multiply	Moderate	Low	No
Salmonella typhi	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
Shigella spp.	High	Short	Low	High	No
Vibrio cholerae	High	Short to long[h]	Low	Low	No
Yersinia enterocolitica	Moderate	Long	Low	Low	Yes
Viruses					
Adenoviruses	Moderate	Long	Moderate	High	No
Enteroviruses	High	Long	Moderate	High	No
Astroviruses	Moderate	Long	Moderate	High	No
Hepatitis A virus	High	Long	Moderate	High	No
Hepatitis E virus	High	Long	Moderate	High	Potentially
Noroviruses	High	Long	Moderate	High	Potentially
Sapoviruses	High	Long	Moderate	High	Potentially
Rotavirus	High	Long	Moderate	High	No
Protozoa					
Acanthamoeba spp.	High	May multiply	Low	High	No
Cryptosporidium parvum	High	Long	High	High	Yes
Cyclospora cayetanensis	High	Long	High	High	No
Entamoeba histolytica	High	Moderate	High	High	No
Giardia intestinalis	High	Moderate	High	High	Yes
Naegleria fowleri	High	May multiply[i]	Low	Moderate	No
Toxoplasma gondii	High	Long	High	High	Yes
Helminths					
Dracunculus medinensis	High	Moderate	Moderate	High	No
Schistosoma spp.	High	Short	Moderate	High	Yes

Note: Waterborne transmission of the pathogens listed has been confirmed by epidemiological studies and case histories. Part of the demonstration of pathogenicity involves reproducing the disease in suitable hosts. Experimental studies in which volunteers are exposed to known numbers of pathogens provide relative information. As most studies are done with healthy adult volunteers, such data are applicable to only a part of the exposed population, and extrapolation to more sensitive groups is an issue that remains to be studied in more detail.

[a] This table contains pathogens for which there is some evidence of health significance related to their occurrence in drinking-water supplies. More information on these and other pathogens is presented in chapter 11.

[b] Health significance relates to the severity of impact, including association with outbreaks.

[c] Detection period for infective stage in water at 20°C: short, up to 1 week; moderate, 1 week to 1 month; long, over 1 month.

[d] When the infective stage is freely suspended in water treated at conventional doses and contact times and pH between 7 and 8. Low means 99% inactivation at 20°C generally in <1 min, moderate 1–30 min and high >30 min. It should be noted that organisms that survive and grow in biofilms, such as *Legionella* and mycobacteria, will be protected from chlorination.

[e] From experiments with human volunteers, from epidemiological evidence and from animal studies. High means infective doses can be $1–10^2$ organisms or particles, moderate $10^2–10^4$ and low $>10^4$.

[f] Includes enteropathogenic, enterotoxigenic and enteroinvasive.

[g] Main route of infection is by skin contact, but can infect immunosuppressed or cancer patients orally.

[h] *Vibrio cholerae* may persist for long periods in association with copepods and other aquatic organisms.

[i] In warm water.

(Reproduced from WHO, 2006)

Comparison of Chlorine Compounds Used for Disinfection

Chlorine gas is commonly found in developed countries. However, hypochlorites are more common in developing countries for disinfection because of their wide availability, ease and safety of handling, and simplicity of requisite feed systems (Harris, 1992). Available hypochlorites include sodium hypochlorite (chlorine bleach), usually in liquid form, chlorinated lime (bleaching powder), usually in solid form, and calcium hypochlorite (HTH-high test hypochlorite) also usually available in the solid forms of powder, tablets, or granules (Harris, 1992; Richardson, 2004; Skinner, 2001). The various chlorine compounds available in the developing world are reviewed in Table 4.

Table 4: Description of Chlorine Compounds' Common Name, Chemical Formula, Form, and Percent Active Chlorine by Mass

Compound	Common Name	Chemical Formula	Form	Percent active chlorine by mass (%)
Dilute sodium hypochlorite	Household bleach	Solution of sodium hypochlorite	Liquid	1-5
Sodium hypochlorite		NaOCl	Liquid	10-15
Chlorinated lime	Bleaching powder	$CaO*2CaOCl_2*3H_20$	Solid	25-35
Calcium hypochlorite	High-test hypochlorite	$Ca(OCl)_2*4\ H_20$	Solid	60-70

Sodium hypochlorite can be used both in small scale water systems and in the home (WHO, 2000). Containing 10-14% available chlorine, sodium hypochlorite can be highly toxic and hazardous (Skinner, 2001; Richardson, 2004). Diluted into household bleach, the substance is more stable. However, it has the potential to be corrosive, gives off gas, and loses 10% of available chlorine in 10 days (Harris, 1992). Also, it can be stored no more than 4-6 weeks, with a maximum shelf life of 60-90 days (WHO, 1993). However, with proper storage, avoiding exposure to light and heat, it can last several months (Skinner, 2001). Thus, bulk purchases and long-term storage are not advisable (Harris, 1992).

Another type of chlorine disinfectant is chlorinated lime. Containing 25-37% available chlorine, it also decomposes rapidly with rising temperature, moisture, and light (Skinner, 2001; WHO, 1993). Chlorinated lime and quicklime are more stable at high temperatures, with only 25-30% available chlorine (Harris, 1992). It is recommended to dissolve the chlorinated lime into solution to 2% available chlorine before entering water (WRC, 1984).

Calcium hypochlorite, a more stable chlorine compound, contains 60-70% available chlorine. It has the positive characteristics of easy transport and storage potential (Harris, 1992). It can be in the form of a pure powder; tablets are not in the pure form in order to reduce the absorption of moisture. It is recommended to store calcium hypochlorite in a cool, dry, airtight container to reduce absorption of moisture (Skinner, 2001).

Comparison of Chlorine Delivery Options in to Water System

Chlorine delivery to the water system is usually classified into three categories: gravity-driven, water-powered, and diffusion-based. Gravity-driven options include: Mariotte Jar; inverted bottle with water seal; constant-head tanks; inverted bottle with floating valve; floating draw-off; and Vandos chemical feeder. Water-powered chlorinators are wheel feeder dosers, floatpowered chemical doser, hydraulic motor/piston driven dosers, Venturi-powered dosers, Direct suction dosers, Displacement-bag doser. Lastly, diffusions-based options include Pot chlorinators and floating chlorinators, Continuous flow diffusers, Intermittent flow diffusers (Skinner, 2001). In the developing world, options are sometimes limited by the lack of electricity.

One particular gravity-driven chlorinator that does not require electricity and still provides relatively accurate dosing is the Pulsar 1 unit, originally used in chlorinating pools using calcium hypochlorite tablets, but this time adapted to the developing world in Ghana. The study noted technical feasibility, but with challenges in training for operation and maintenance of the Pulsar 1 unit because of its technical complexity. Also, the majority of testing took place in the United States; the implementation and testing of the unit took place during a three week trip to Ghana and not studied over the long term for durability of the unit, training of the operator, or change in flow or water quality due to seasonal variability (Cash-Fitzpatrick, 2008).

Comparison of Chlorine Concentration Testing Options

Chlorine concentration testing has multiple functions. One, it can be used in conjunction with coliform testing to help in dosing instead of modeling (Gibbs et al, 2006). Concentration testing is used to determine the effectiveness of chlorine in disinfection. Chlorine reacts with organics, metals, ammonia, sulfides, and bacteria, thus the concentration records the chlorine left in the system after reacting with the above mentioned items.

In order to test the chlorine concentration, a variety of options are available. The DPD (N,N Diethyl-1,4 Phenylenediamine Sulfate**)** method is the most common, reacting with chlorine to change the color of the liquid (Wilde, 1991; Skinner 2001; Reed, 2005). Two DPD testing methods exist--the color-wheel or the digital colorimeter. The color wheel, or comparator, is affordable, but relies on subjective measurement, thus training is needed to ensure consistency in data. The color wheel can be accurate to 0.1 mg/L (Reed, 2005; Skinner, 2001). The second option, the colorimeter is more expensive up front and per test, but is quick, easy, and offers high level precision when calibrated (Harp, 2002). The DPD method is compared with other methods in Table 5.

One notable company that produces field water quality testing kits is the HACH Company (Loveland, CO). Table 6 compares the color comparison and digital colorimeter in a variety of categories. In this study, the HACH Pocket Colorimeter II Test Kit, using the DPD Colorimetric method, was used because of its quick and precise measurements.

Table 5: Comparison of Analytical Methods for Chlorine by Analysis Range, Detection Level, Estimated Precision, Application, and Skill Level
(Adapted from Harp, 1995)

Method	Analysis Range (mg/L)	Detection Level (mg/L)	Estimated Precision (% RSD)	Application
DPD Colorimetric	0-5	0.005	1-2	Free and Total
ULR-DPD Colorimetric	0-0.5	0.002	5-6	Total
DPD Titration	0-3	0.018	2-7	Free and Total
Iodometric	Up to 4%	1	NR	Total Oxidants

Table 6: Comparison of HACH Chlorine Testing Products by Type, Measurement, Range, Increment, Price, and Reagent Price (Adapted from HACH, 2011)

Product	Type	Measurement	Range (mg/l)	Increment (mg/l)	Price	Reagent Price	Note
Free and Total Chlorine Test Strips	Color Comparison	Free Cl, Total Cl	0-10	0.5,1.0,2.0,4.0,10.0*	N/A	$14.99/50 tests	Only strips needed
CN-66F Chlorine Test Kit, Color (Includes reagent for 100 tests)	Color Comparison	Free Cl	0-3.4	0.1	$45.79	$17.50/100 tests	
CN-66 Chlorine Test Kit, Color Disc (Includes reagent for 50 free and 50 total tests)	Color Comparison	Free Cl, Total Cl	0-3.4	0.1	$52.29	$33.05/200 tests**	Separate reagents needed for free and total
CN-70 Chlorine Test Kit, Color Disc (Includes reagent for 100 tests)	Color Comparison	Free Cl, Total Cl	0-0.7	0.02	$68.39	$43.65/100 tests	Free and total measured with same reagent
			0-3.4	0.1			
CN-80 Chlorine Test Kit, Color Disc (Includes reagent for 100 tests)	Color Comparison	Free Cl, Total Cl	0-0.7	0.02	$101.00	$43.65/100 tests	Free and total measured with same reagent
		Free Cl, Total Cl	0-3.5	0.1			
		Total Cl (only)	0-10	0.5			
Pocket Colofimeter II Test Kit (Includes reagent for 100 low range or 50 high range)	Digital Colorimeter	Free Cl, Total Cl	0.02 -2.00	0.02	$389.00	$15-$25/100 tests***	Separate reagents needed for free and total
		Free Cl, Total Cl	0.1-8.0	0.1			
Pocket Colofimeter II Test Kit w/ pH test (Includes reagent for 100 low range or 50 high range)	Digital Colorimeter	Free Cl, Total Cl	0.02 -2.01	0.18	$395.00	$21.89/100 tests	Separate reagents needed for free and total
		Free Cl, Total Cl	0.1-8.1	0.26			

*Colors indicate one of the listed concentration steps, there is no measurement of concentrations between the steps

**100 free chlorine tests and 100 total chlorine tests

***See www.hach.com for more information

Comparison of Chlorine Concentration Monitoring and Modeling Options

With increased technology, knowledge, materials, and capacity in the developing world, water system operators are likely to look for better ways to effectively analyze the inactivation of pathogens using chlorine in their water systems. Chlorine not only decays, but also reacts with organic and inorganic material, biofilms attached to pipe walls, and corroded pipe materials before reaching the user (Vasconcelos et al., 1997). The ability to model data will help predict chlorine concentration levels within a system as the chlorine is consumed, thus helping with the operation of a system to deliver disinfected water to the community. Many theoretical models and applications of chlorine concentration modeling exist, but none have been applied in the developing world setting.

In the developed world, two types of modeling frameworks exist. The first is the Process-Based Modeling Framework. To produce the process-based type of model that accurately portrays how chlorine reacts in a water system, "a good understanding of the system…along with extensive, accurate data to produce the hydraulic model used to determine travel times of water in the system" is required (Gibbs et al., 2006). The data is harder to obtain in the developing world because of variability in water supply flows due to seasonal variation and weather patterns and changing usage trends due to, for example, seasonal working schedules. This process-based method requires "extensive and accurate data regarding numerous water quality parameters… [making] development of mathematical water quality models quite challenging" (D'Souza and Kumar, 2010). The framework models the decay of chlorine in its reactions interacting with substances in the water (bulk-decay) and with the pipe surfaces (wall-decay) to produce most-commonly first order exponential decay equations. The wall-decay reactions are modeled with existing data on pipe material, initial chlorine concentration, flow velocity, corrosion, and biofilm to produce the coefficients for the models (Huang, 2007).

The second type of model is called the Data-Driven Statistical Model. It is often used in situations when data of the water system is imprecise, difficult to obtain or unavailable, a common situation in the developing world. The statistically based models are based on dependent and independent variables like temperature, flow rates, and chlorine input. One example of a data-driven model is an artificial neural network, which can predict the chlorine decay between two points by using historical data to "identify the intricacies of a process and discover and establish complex non-linear relationships between input and output variables" (Gibbs et al., 2006; Rodriguez, J. West, Powell, & Serodes, 1997). Both the process-based model and the data-driven model are applicable but not been used in the developing world.

Application of Field Free Chlorine Concentration to Ct Values

As discussed previously, multiplying the chlorine concentration by the contact time results in the Ct value—the higher the value, the more resistant to disinfection the pathogen is.

With the values of free chlorine concentration, contact time, and pH, conclusions can be drawn to previous studies (Figure 4) as to the effectiveness of the disinfection in inactivating key pathogens. In Figure 4, disinfection of *E. coli* present in water with a pH of 7 requires a Ct of 0.1, disinfection of Hepatitis A requires a Ct of 10, and disinfection *E. histolytica* with a ph of 7 requires a Ct of 35.

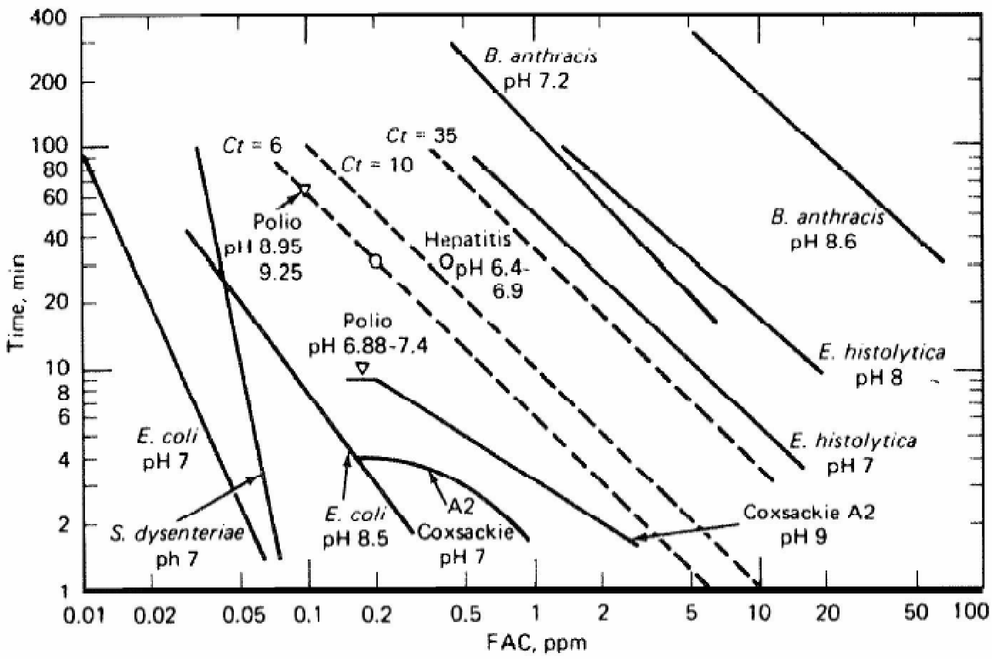

Figure 4: 2 Log Disinfection of Selected Microorganisms by Free Chlorine in Terms of Time, and pH
(Reproduced from WHO, 2004)

Table 7 provides a summary of a variety of studies on different pathogens to find their appropriate Ct value, which is used in comparison to the results of the field studies that measured free chlorine in this study. In this table, Ct values are listed as < 0.25 mg x min/L for *E. coli*, 1 mg x min/L for *Salmonella typhi*, < 0.41 mg x min/L for Hepatitis A, and < 15 mg x min/L for *Giardia lamblia*. In intervention contexts, the chlorinator could be applied to urban areas after storage tanks in a distribution system. Therefore, this study will include values for *Vibrio cholerae* (<0.5) and Rotavirus (0.05).

In conclusion, previous studies have been done in the developed world on concentration and contact time of chlorine as well as advanced modeling of disinfection of water supply systems, but the application of the Ct method and modeling to rural gravity flow water systems in Panama and other developing world locations to study the effectiveness of an in-line chlorinator is unique.

Table 7: Safe Water's Table of Drinking Water Quality Characteristics and Ct Values for Common Bacteria, Viruses, and Protozoa. Pathogens common to Panama include *E. coli*, *Salmonella typhi*, Hepatitis A, *Giardia lamblia*, and *E. histolytica*. *Vibrio cholerae*, Rotavirus are also used because of their applicability to cases of intervention. (Reproduced from Center for Disease Control, 2007)

PATHOGEN	FROM WHO GUIDELINES FOR DRINKING-WATER QUALITY				CONCENTRATION OF CHLORINE (MG/L)	TIME OF CHLORINE EXPOSURE (MIN)	CT FACTOR	% INACTIVATION	VARIABLES AFFECTING CT FACTOR		PATHOGEN SUBCLASSIFICATION AND/OR EXPERIMENTAL DESIGN	SOURCE
	Health significance	Persistence in water supplies	Resistance to chlorine	Relative infectivity					Temp (°C)	pH		
BACTERIA												
Burkholderia pseudomallei	Low	May multiply	Low	Low	1.0	60	**60**	99%	22.0-25.0	6.25-7.0	45 pooled clinical and environmental samples	Howard, 1993
Campylobacter jejuni	High	Moderate	Low	Moderate	0.1	5	**0.5**	99-99.9%	25.0	8.0	Serotypes PEN1, PEN2, PEN3 isolated from patients	Blaser, 1986
Escherichia coli	High	Moderate	Low	Low	0.5	<0.5	**<0.25**	99.999999%	23.0	7.0	Strain ATCC 11229	Zhao, 2001
E. coli (enterohemorrhagic)	High	Moderate	Low	High	0.5	<0.5	**<0.25**	99.98-99.999999%	23.0	7.0	Strains isolated from six human patients	Zhao, 2001
Salmonella typhi	High	Moderate	Low	Low	0.05	20	**1**	99.2%	20-25	7.0	Two isolates – one from patient blood sample	Butterfield, 1943
Shigella dysenteriae.	High	Short	Low	Moderate	0.05	<1	**<0.05**	99.9%	20-25	7.0	Three isolates from patient stool samples	Butterfield, 1943
Shigella sonnei	-	-	-	-	0.5	1	**0.5**	99%	25.0	7.0	Water Engineering Research Laboratory isolate	King, 1988
Vibrio cholerae (smooth strain)	High	Short	Low	Low	0.5	<1	**<0.5**	100%	20.0	7.0	O1 El Tor Inaba strain N16961	Morris, 1993
Vibrio cholerae (rugose strain)	High	Short	Low	Low	2.0	20	**40**	99.999%	20.0	7.0	O1 El Tor Inaba strain N16961/Ru	Morris, 1993
Yersinia enterocolitica	High	Long	Low	Low	1.0	>30	**>30**	82-92%	20.0	7.0	3 strains: ATCC 9610 O:8, 632 O:25,35 and IM 69/85 O:3 Lis VIII	Paz, 1993
VIRUSES												
Enteroviruses												
Coxsackie A	High	Long	Moderate	High	0.46-0.49	0.3	**0.14-0.15**	99%	5.0	6.0	Coxsackie A9	Engelbrecht, 1980
Coxsackie B	High	Long	Moderate	High	0.48-0.50	4.5	**2.16-2.25**	99%	5.0	7.81-7.82	Coxsackie B5	Engelbrecht, 1980
Echovirus	High	Long	Moderate	High	0.48-0.52	1.8	**0.86-0.94**	99%	5.0	7.79-7.83	Serotype 5	Engelbrecht, 1980
Hepatitis A	High	Long	Moderate	High	0.41	<1	**<0.41**	99.99%	25.0	8.0	Strain from one patient sample	Grabow, 1983
Poliovirus	High	Long	Moderate	High	0.5	12.72	**6.36**	99.99%	5.0	6.0	Poliovirus type 1	Thurston-Enriquez, 2003
Adenoviruses	High	Long	Moderate	High	0.17	4.41	**0.75**	99.99%	5.0	7.0	Adenovirus 40	Thurston-Enriquez, 2003
Noroviruses	High	Long	Moderate	High	1.0	0.07	**0.07**	99.99%	5.0	7.0	Feline calicivirus used as a model	Thurston-Enriquez, 2003
Rotavirus	High	Long	Moderate	High	0.20	0.25	**0.05**	99.99%	4.0	7.0	Human rotavirus type 2 (Wa)	Vaughn, 1986
PROTOZOA												
Entamoeba histolytica	High	Moderate	High	Low	2.0	10	**20**	99%	27-30	7	Viability assessed by in vitro excystation assay	Stringer, 1975
Giardia lamblia	High	Moderate	High	Low	1.5	10	**15**	99.9%	25.0	7.0	Viability assessed by excystation	Jarroll, 1981
Toxoplasma gondii	High	Moderate	High	Unknown	100	1440	**>144,000[1]**	-	22.0	7.2	Viability assessed by mouse bioassay	Wainwright, 2007
Cryptosporidium parvum	High	Long	High	Low	80	90	**7,200[1]**	99%	25.0	7.0	Viability assessed by excystation and mouse viability assays	Korich, 1990

Chapter 3: Materials and Methods

Location of Field Study

The two communities studied in this research are Calabazal and Quebrada Mina. Both communities are served by gravity flow water supply systems. Figure 5 shows their relative location to each other.

The Comarca Ngabe Bugle is situated in western Panama, where the Cordillera mountain range divides the Comarca Ngabe Bugle in two—the one half located on the northern Caribbean side and the other located on southern Pacific side. Most of the aqueducts in the Comarca Ngabe Bugle are gravity-fed water systems that originate from springs. The two systems selected for this study, Calabazal and Quebrada Mina, shown in Figure 5, are fairly representative of most water systems in the area. Both systems have chlorinators placed upstream from the storage tank and receive more flow in the wet season (April to December) and less flow in the dry season (December to April). For more information on the components and construction of gravity flow water systems and spring box design, please see Mihelcic et al. (2009).

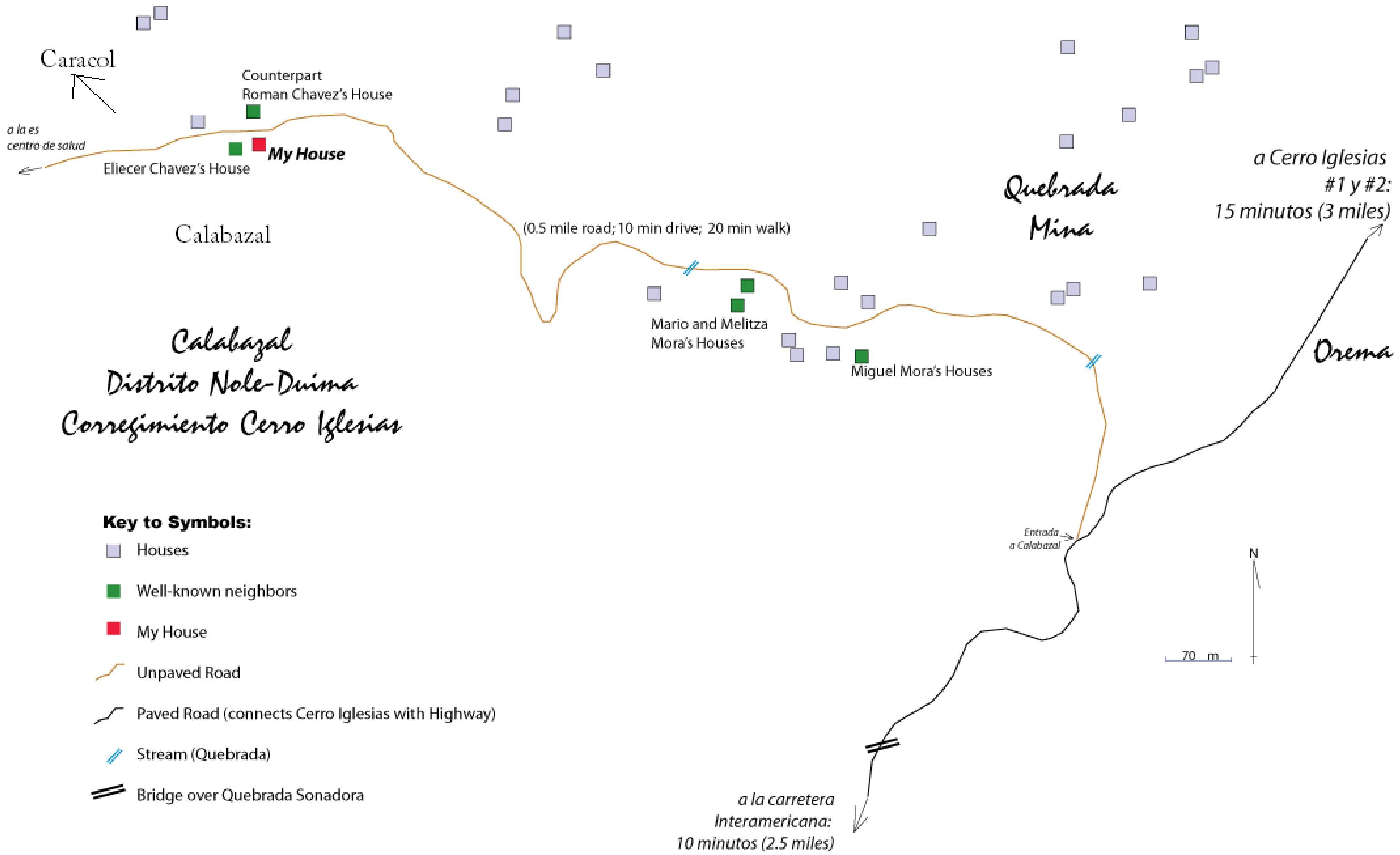

Figure 5: Map of Calabazal, Quebrada Mina, and Surrounding Communities

The Panama Ministry of Environmental Health (MINSA) in San Felix supplies a materials list for construction of the chlorinator along with chlorine tablets (Appendix A). The community is responsible for purchasing the materials and constructing the chlorinator. The water system is managed by a local water committee, made up of a president, vice president, treasurer, secretary, and two messengers, all who are members of the community. It is common for each committee member to serve for two years before a new committee is elected. If there are any problems that the community is unable to resolve, MINSA is able to provide technical support.

Quebrada Mina is an indigenous community of 140 people. It is located just off the newly paved road heading to the larger town of Cerro Iglesias. In 2009, a Peace Corps Volunteer worked with community leaders and the NGO Waterlines, to construct a new aqueduct, connecting 25 houses to two springs. A storage tank was built, sprouting two main lines that lead to the community. In order to maintain the aqueduct, the water committee organizes regular water meetings and workdays, which require all households connected to the aqueduct to send one representative to attend and participate.

Calabazal is a neighboring community located approximately ten minutes away from Quebrada Mina by walking east. It is home to 325 residents and has a primary school and health post. The aqueduct system, built in 2001 with the help of the local government, has 25 house connections. Water from a spring is captured by a spring box, transported to a storage tank, and then split into three main lines to the community. The chlorinator was installed on October 8, 2010, just up the line from the tank. Table 8 compares the gravity flow water systems of Quebrada Mina and Calabazal. Quebrada Mina has a newer water system with less beneficiaries, but the system is a little more spread out. Water enters the storage tank from two separate transmission lines, one carrying water from one spring and the other carrying water from two springs. The Quebrada Mina system has the chlorinator installed on only one transmission line up line from the 3,000 gallon storage tank.

Table 8: Comparison of Quebrada Mina and Calabazal Gravity Flow Water Systems in Terms of Year Built, Number of Beneficiaries and Households, and Physical Characteristics of the Water Systems

	Quebrada Mina	**Calabazal**
Year Built	2009	2001
Number of Beneficiaries	140	325
Number of Households	25	40
Type of Water Source	3 springs	1 spring
Distance to Last House on Line	1,400m	300m
Size of Storage Tank	3,000 gal	3,000 gal
Number of House Connections	25	25
Location of Chlorinator	Up line from tank	Up line from tank

Physical Description and History of MINSA's In-Line PVC Chlorinator

The chlorinator is essentially a PVC cylinder with a screw-on top, where a chlorine tablet can be inserted in the cylinder and the top screwed back on. It is recommended to place the chlorinator directly into the line right upstream from the storage tank to achieve sufficient contact time for the chlorine. Figure 6 shows how as the water passes by the chlorinator, the 3-inch chlorine tablet slowly dissolves into the water.

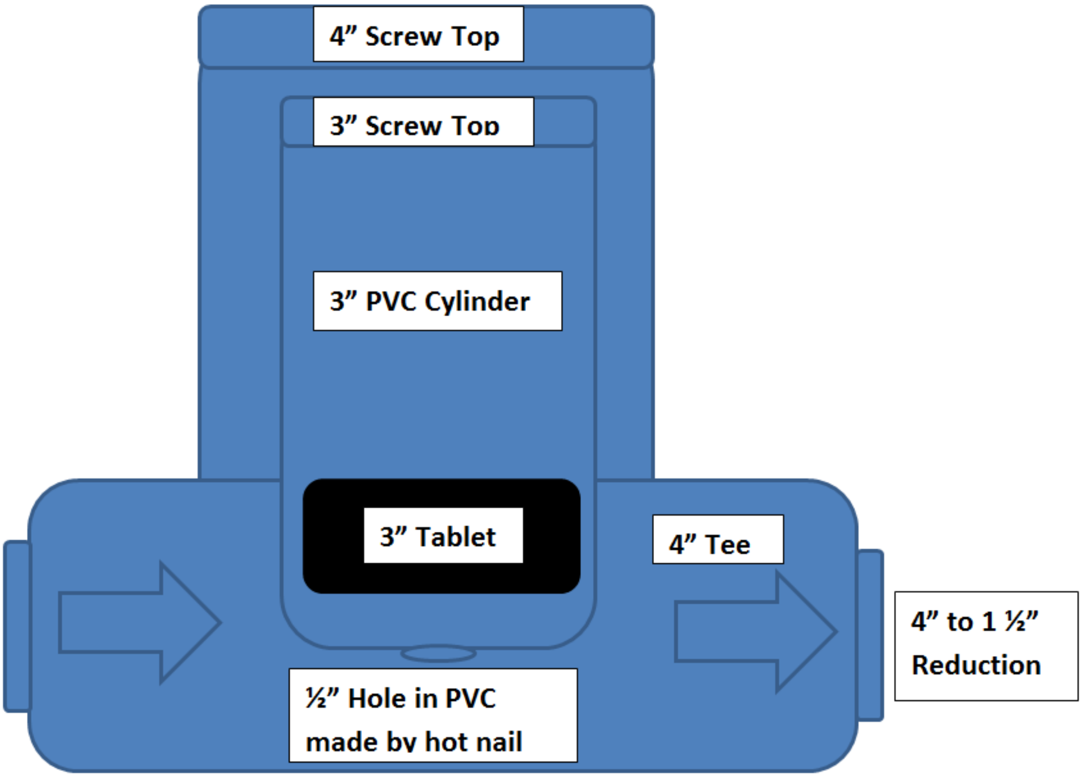

Figure 6: Design of the Panama Ministry of Environmental Health’s (MINSA) In-Line PVC Chlorinator. The ½” hole can be enlarged to increase flow into the 3” PVC cylinder. The reduction can be changed depending on the diameter of tube of the transmission line.

A MINSA technical worker mentioned to this study’s author that before 1998, MINSA recommended the use of a 55-gallon drip chlorinator tank that was placed on top of the water tank (see Mihelcic et al., 2009 for description). After problems of chlorinator tanks not being used and maintained properly in the Comarca Ngabe Bugle due to lack of training and interaction with the agency, MINSA searched for a different solution—the in-line chlorinator. The in-line chlorinator is not an officially approved and tested design by MINSA, just a technology they believe could be more effective in the Comarca Ngabe Bugle. There is space in the chlorinator for more than one tablet to be added.

The chlorinator does not have a stated maximum flow it can handle; however, the amount of chlorine that dissolves into the water can be adjusted by the size, quantity and location of holes in the PVC container that holds the chlorine tablet (e.g., ½ inch hole in Figure 6). The holes are normally just under ½ inch in diameter.

The chlorine tablets are manufactured by the company Provichlor, part of Ruequim (Morelia, Mexico). Each tablet is three inches in diameter, weighs 200 grams, is reported to contain 60% calcium hypochlorite ($Ca(OCl)_2$) (by weight), and is designed to have 2 grams of tablet dissolved into every 1,000 liters of water to ensure that the concentration is above the minimum concentration of 1 mg/L. At the start of testing, tablets were provided from MINSA to the study's author through an unsealed clear hard plastic cylinder, holding approximately 10 tablets. Accordingly, some tablets were not adequately protected from the humidity—the author observed that when placed in water for five minutes, they promptly broke apart upon touch. MINSA then delivered the tablets in individually wrapped plastic packages, the recommended manner for storage because the chlorine does not have the ability to react with moisture in the air.

The Comarca MINSA office receives money from MINSA in Panama City to purchase the tablets. The tablets are purchased for $2 a piece from a retailer in the nearby city of David. The tablets were initially sold for $1 a piece in the Comarca Ngabe Bugle, but the water committees were reluctant to purchase the tablets as they were unsure of the benefits. MINSA now distributes the tablets for free to ensure more regular use.

Figures 7a-d display the process of installing the chlorinator into the aqueduct, shown from the installation in Calabazal in October 2010.

Figure 7: MINSA PVC Chlorinator in the Field. Clockwise from upper left:
a) 3¨ diameter chlorine tablet being added to 3" PVC capsule; b) 3¨ PVC capsule inside 4" Tube; c) PVC chlorinator in the field; d) Chlorinator installed below ground surface upstream of water storage tank

Methods

During each round of testing, free chlorine and total chlorine concentration were measured every time at each sampling location. The chlorine concentration (free and total chlorine) was determined using a HACH Pocket Colorimeter II (Cat. No. 58700-00). Low range testing occurs within the range of 0.02-2.00 mg/L and high range 0.1-8.0 mg/L. This HACH Pocket Colorimeter II tests for free chlorine and total chlorine concentration using the DPD (N,N Diethyl-1,4 Phenylenediamine Sulfate**)** method, a USEPA accepted method, that uses powder pillows as an indicator (APHA, 2005). To measure free chlorine, the DPD in the pillow is oxidized by the chlorine (added as calcium hypochlorite) in the water, causing the water to turn a magenta color. DPD can also react with bromine, chlorine dioxide, hydrogen peroxide, iodine, ozone and permanganate, creating a false positive. To determine total chlorine, potassium iodide is added, which then is oxidized by the chloramines. This reaction results in iodine, which reacts with DPD and turns the water a magenta color. The pillows have an estimated detection limit of 0.1 mg/L. DPD Chlorine Spec Color Standards (Cat. 26353-00) of 0.23, 0.94, and 1.63 mg/L were obtained and used from HACH Company to ensure that the instrument was working consistently and properly.

Other factors that could affect the chlorine concentration downstream from the chlorinator, such as temperature and flow rate, were also measured. Turbidity measurements were not taken as an instrument was unavailable. The temperature was measured at every location that a sample was collected for analysis of chlorine during the Field Study 1. The flow was measured entering the storage tank at the beginning of each field study. Additionally, the tablet weight was also measured at the beginning of each time period for which sampling of chlorine occurred. Tables and figures regarding temperature, flow, and tablet weight are provided in Appendix B.

Testing Procedure for Field Study 1 (April 28-30)

After recording the dry weight of the tablet, the tablet was inserted into the chlorinator and removed after one hour to record the wet weight. The temperature was measured by collecting a 1,000-mL sample and inserting an environmental thermometer into the sample for one minute before reading the result. Free chlorine and total chlorine concentration were measured at the source (i.e., spring), entering the storage tank two meters downstream from the chlorinator, leaving the storage tank, the first house, the middle house, and the last house on the transmission line. All chlorine measurements were done in duplicate. This process of recording the wet weight of the tablet and testing for free and total chlorine was then repeated two days later. As the results were obtained from Field Study 1, the procedure was modified slightly for the subsequent field studies. The changes in the experimental plan, made in an attempt to achieve better results in future rounds, are provided in Table 9, and included sampling more frequently, using dilutions, and obtaining only one sample instead of two. When the tablets were not sealed in a plastic wrapper before use, the entire tablet dissolved in a matter of hours. Testing took place around every two hours for one day. When the tablets were sealed in plastic wrapper before use, the tablet dissolved in approximately one week.

In this case, testing occurred every twenty-four hours until the concentration fell below the detection limit.

Table 9: Summary of Procedural Changes after Field Study 1

	Field Study 1	**Field Study 2**	**Field Studies 3 & 4**	**Field Studies 5-7**
# of chlorine tests made at each point	2	2	2	2
Time Intervals (hr) between sampling	2,24,48	1,3,5,8,24	1,3,5,8,24, 25,27,29,32,48	2, 1 day, 2 days, 3 days, 4 days,5 days, 6 days, 7 days
Gathering of sample for Total Chlorine measurement	5 min after free chlorine	Same time as free chlorine	Same time as free chlorine	Same time as free chlorine
Dilutions used before analysis for chlorine	None	Yes (1/10)	Yes (1/10)	None
pH Test	Yes	Yes, only at 1hr	Yes, only at 1hr	None
Temperature measured	Yes	None	None	None
New Tablet added at 24 hours	No	No	Yes	No

Free Chlorine and Total Chlorine Concentration Testing Procedure

For samples collected at the spring, a 100-mL beaker was filled from the cleanout valve after confirming the presence of no sediment and then letting the water run for 15 seconds. When testing the water entering the tank, the 100-mL beaker was filled from the water entering the tank through the inlet pipe. Leaving the tank, the sample was collected from the storage tank's cleanout valve after 15 seconds and confirming no sediment. A 100-mL sample was collected in a glass beaker from the faucets of the homes after water was run for fifteen seconds. Two 10-mL cells provided by HACH were filled using the 100-mL sample, serving as blanks. The meter cap was removed from the HACH Pocket Colorimeter II, the first blank was placed in the cell holder and the cap was placed over the cell compartment. The blank was then zeroed, the blank removed, and the contents of one DPD Free Chlorine or Total Chlorine Powder Pillow were added to the blank. The cell was shaken for 20 seconds, was wiped down of excess liquid or fingerprints with a dry towel, and then returned to the cell holder and covered with the cap. The enter key was pressed after one minute in order to obtain the free chlorine concentration. This procedure was repeated for the second blank. After thoroughly rinsing the two cells with water from the faucet, the procedure was repeated to obtain the total chlorine concentration. All free chlorine and total chlorine concentration results reported are the average of two measurements obtained from one sample. Apart from the chemical added, the only difference between the free chlorine and total chlorine analysis was that the measurement for total chlorine requires a waiting period of four minutes instead of one minute.

Flow Testing Procedure

A 1,000-mL container was used to measure the flow rate because this size fit best in the limited space available to measure flow in to the full storage tank. The container was used to collect all the water entering the tank until the container was filled while a stopwatch measured the time elapsed. This procedure was repeated twice and the results were averaged.

Tablet Weight Testing Procedure

A kitchen scale was used to measure the weight of the tablet at the beginning of each testing period. The scale was placed on a level surface and zeroed. Next, a dry tablet was placed on the scale until the reading steadied, usually after about three seconds. Readings were obtained before initially placing a new tablet in the chlorinator, after five minutes submerged in water, and then during every testing period. The wet tablet was dried by gently shaking the tablet until all excess water was removed. The tablet was weighed after sampling the water entering the tank and before sampling the water leaving the tank so that the chlorine concentration readout entering the tank wouldn't be affected by the tablet not being present for two or three minutes.

Location of Testing

Initially, two communities' water systems were tested, Calabazal and Quebrada Mina. After receiving similar results from both communities (Field Studies 1-2), further testing was only conducted in Calabazal due to its closer proximity between sampling locations (Field Studies 3-7).

In Calabazal and Quebrada Mina, the testing occurred at the spring (before the chlorinator), entering the water storage tank (2 m after the chlorinator), leaving the storage tank, the first house, the middle house, and the last house along the transmission line. Testing required approximately two hours to test at all locations. Once results continuously confirmed no detection of chlorine at the spring, the testing for chlorine concentration was discontinued at that location. The distances between testing locations in Calabazal are provided in Table 10, and a map of Calabazal aqueduct that shows sampling locations is provided in Figure 8. The distances between testing locations in Quebrada Mina are provided in Table 11 and a map of the Quebrada Mina aqueduct that shows sampling locations is provided in Figure 9. A summary of the testing dates and quantity of samples is shown in Table 12.

Table 10: Distance between Testing Locations for Calabazal Aqueduct

Starting Location	Ending Location	Distance (m)
Spring	Tank	661
Tank	First House	23
First House	Middle House	143
Middle House	Last House	177

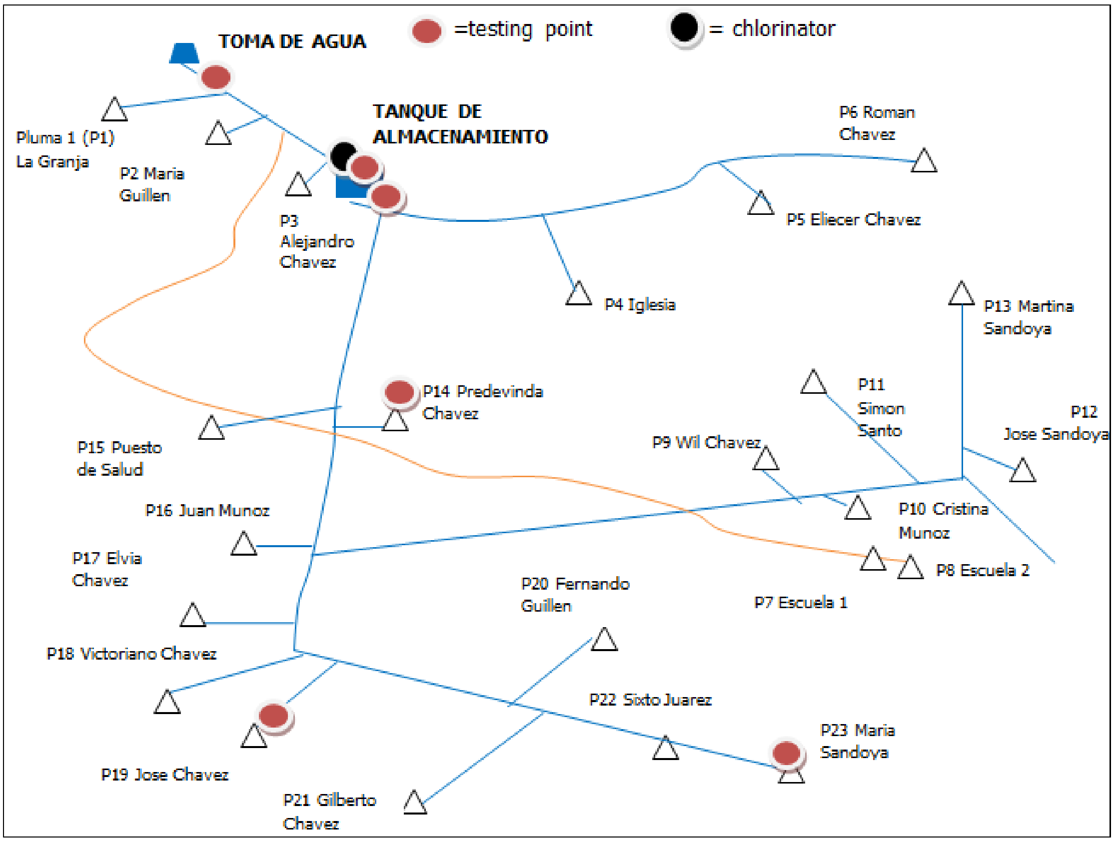

Figure 8: Water System Map for Village of Calabazal Showing Sampling Locations (Red Circles) and Location of Chlorinator (Black Circle). The line leading to the school, shown in orange, diverges before the tank and is not chlorinated. The letter P represents pluma, the word for faucet in Spanish.

Table 11: Approximate Distance between Testing Locations for Quebrada Mina Aqueduct

Starting Location	Ending Location	Distance (m)
Spring	Tank	300
Tank	First House	240
First House	Middle House	630
Middle House	Last House	597
Spring	Last House	1767

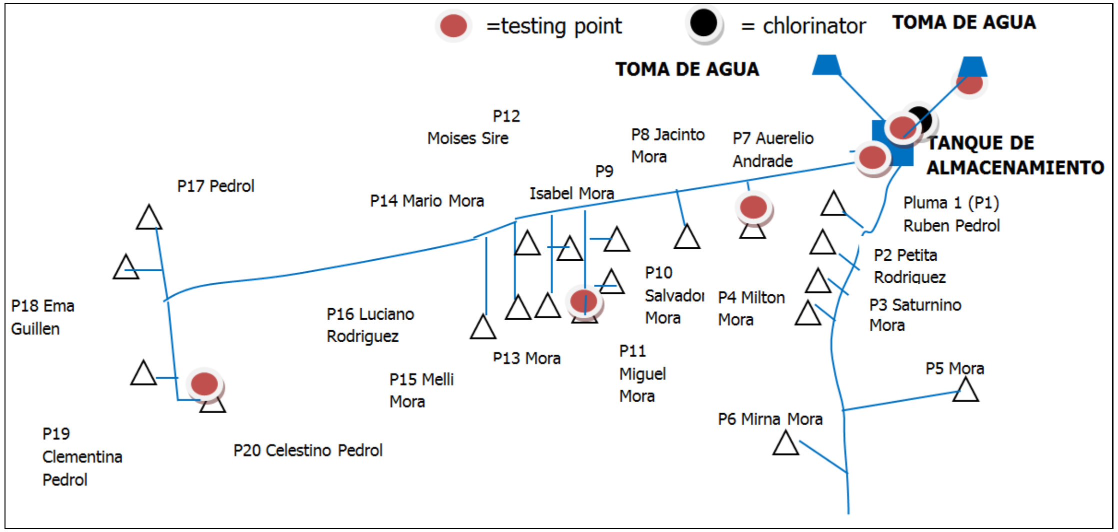

Figure 9: Water System Map for Village of Quebrada Mina Showing Sampling Locations (Red Circles) and Location of Chlorinator (Black Circle). The letter P represents pluma, the word for faucet in Spanish

Table 12: Description of Field Studies 1-7, Including Dates of Study, Tablet Description, and Calculation for Number of Chlorine Tests Needed in Quebrada Mina and Calabazal.

Field Study	Location	Tablet Description	Number of Communities Sampled	Number of Testing Times	Number of Chlorine Measurements	Number of Sampling Locations	Number of Chlorine Tests in Field Study
1: (April 28-30)	Calabazal Q. Mina	One Tablet Without Wrapper	2	3	2	6	72
2: (June 17-20)	Calabazal Q. Mina	One Tablet Without Wrapper	2	5	2	6	120
3: (June 22-23)	Calabazal	One Tablet Without Wrapper	1	5	2	6	60
4: (June 23-24)	Calabazal	One Tablet Without Wrapper	1	5	2	6	60
5: (August 7-14)	Calabazal	One Tablet Stored in Wrapper Before Use	1	8	2	6	96
6: (August 17-24)	Calabazal	One Tablet Stored in Wrapper Before Use	1	8	2	6	96
7: (August 25-September 1)	Calabazal	Three Tablets Stored in Wrapper Before Use	1	8	2	6	96

Chapter 4: Results and Discussion

The results are organized into three sections: results of one tablet installed in the chlorinator that was not provided in a sealed plastic wrapper; one tablet installed in the chlorinator that was stored in the plastic wrapper before use; and three tablets installed in the chlorinator that were stored in the plastic wrapper before use. The one tablet installed in the chlorinator that was not provided in a sealed plastic wrapper section contains results from two communities: Quebrada Mina and Calabazal. Because of similar results in this first study, only the water system of Calabazal was tested for one tablet stored in the sealed plastic wrapper before use and three tablets stored in the sealed plastic wrapper before use. Approximately two hours were needed to test at every testing location in the system, from the spring to the last house on the line.

Although the Ct method utilizes the free chlorine concentration, total chlorine was measured to verify free chlorine measurements. Out of 257 free chlorine concentration measurements, only 23 resulted in measurements that exceeded the measured total chlorine concentration, and only 3 were greater by more than 0.02 mg/L. This suggests the techniques used in the field to measure free chlorine were consistent and accurate. Total chlorine measurements can be found in Appendix B.

Table 13 summarizes the average and standard deviation for free chlorine and total chlorine concentration during Field Studies 5, 6, and 7. The results show a general trend of the total chlorine being approximately 50% higher than free chlorine, indicating the presence of chloramines, a weaker disinfectant, in the water system.

Table 13: Comparison of Free Chlorine and Total Chlorine Concentration Averages and Standard Deviation during Field Studies 5, 6, and 7

Field Study	Free Chlorine Concentration Average (mg/L)	Free Chlorine Concentration Standard Deviation	Total Chlorine Concentration Average (mg/L)	Total Chlorine Concentration Standard Deviation
5	0.09	0.07	0.13	0.08
6	0.10	0.06	0.13	0.07
7	0.21	0.09	0.30	0.11

In Quebrada Mina, the pH increased as water traveled from the spring box (6.8-7.2) to the last house (7.4-7.6), with little variation between Field Studies 1 and 2. In Calabazal, a pH value of 6.8 was measured at every location during every test. The piping is the same, so the difference is likely attributed to the source water.

Temperature was measured in Field Study 1. In Quebrada Mina, cooler temperatures were recorded at the spring (24-25 ^{o}C), increasing up to 30 ^{o}C at some house connections. In Calabazal, the spring recorded temperatures of 25-26 ^{o}C and up to 28 ^{o}C at some houses.

Results of Free Chlorine Concentration Measured in the Quebrada Mina and Calabazal Water System Using One Tablet Installed in the Chlorinator that was not Provided in a Sealed Plastic Wrapper

The results of the free chlorine concentration measured in the Quebrada Mina water system using one tablet installed in the chlorinator without a wrapper is displayed in Figures 10a-b and Tables 14-15. Results of the free chlorine concentration measured in Calabazal are provided in Figures 11a-d and Tables 16-19. Free chlorine concentration was originally tested at the 48 and 72 hour marks because of the recommendation of a MINSA technical worker that tablets should last approximately ten days.

Figure 10a indicates that in Field Study 1 in Quebrada Mina after two hours of contact, over 8 mg/L of free chlorine concentration was measured leaving the tank and at the first house on the line, indicating that the tablet dissolved rapidly during the first few hours after insertion in to the chlorinator. After 24 hours, free chlorine concentrations were measured between 0.06-0.69 mg/L. After 48 hours, chlorine was mostly not present in the system (0.04 mg/L free chlorine leaving the tank, 0.25 mg/L free chlorine at the last house). Beginning in Field Study 2, sampling took place at the 1, 3, 5, 8, and 24 hour marks.

Figure 10b shows results from five samples taken during the first 24 hours after insertion of a new tablet into the chlorinator during Field Study 2. It indicates that the majority of the chlorine entered the tank before the third hour, with all free chlorine concentration exiting the system before testing at 24 hours. A free chlorine concentration of 21 mg/L was recorded entering the tank after 1 hour (flow rate of 3.18 gpm), which then mixed with the non-chlorinated water arriving from the other spring (flow rate of 3.97 gpm) and the water already present in the tank, leaving the tank with a concentration of 1.02 mg/L free chlorine after 1 hour (all flow measurements can be found in Appendix C). After 3 hours, free chlorine concentration ranged from 2.6 mg/L entering the tank to 14.7 mg/L free chlorine at the last house, showing how the chlorine tablet had previously reached its maximum output, therefore resulting in higher free chlorine concentrations at the end of the line and lower free chlorine concentrations closer to the chlorinator. At the 5 hour mark, free chlorine concentrations at the houses ranged from 5.1-12.3 mg/L, then lower again to 4.2-8.7 mg/L after 8 hours. Residents responded to the high concentrations by saying that they would not drink water that tasted like pure chlorine. Free chlorine concentrations at all locations were measured below 0.05 mg/L after 24 hours.

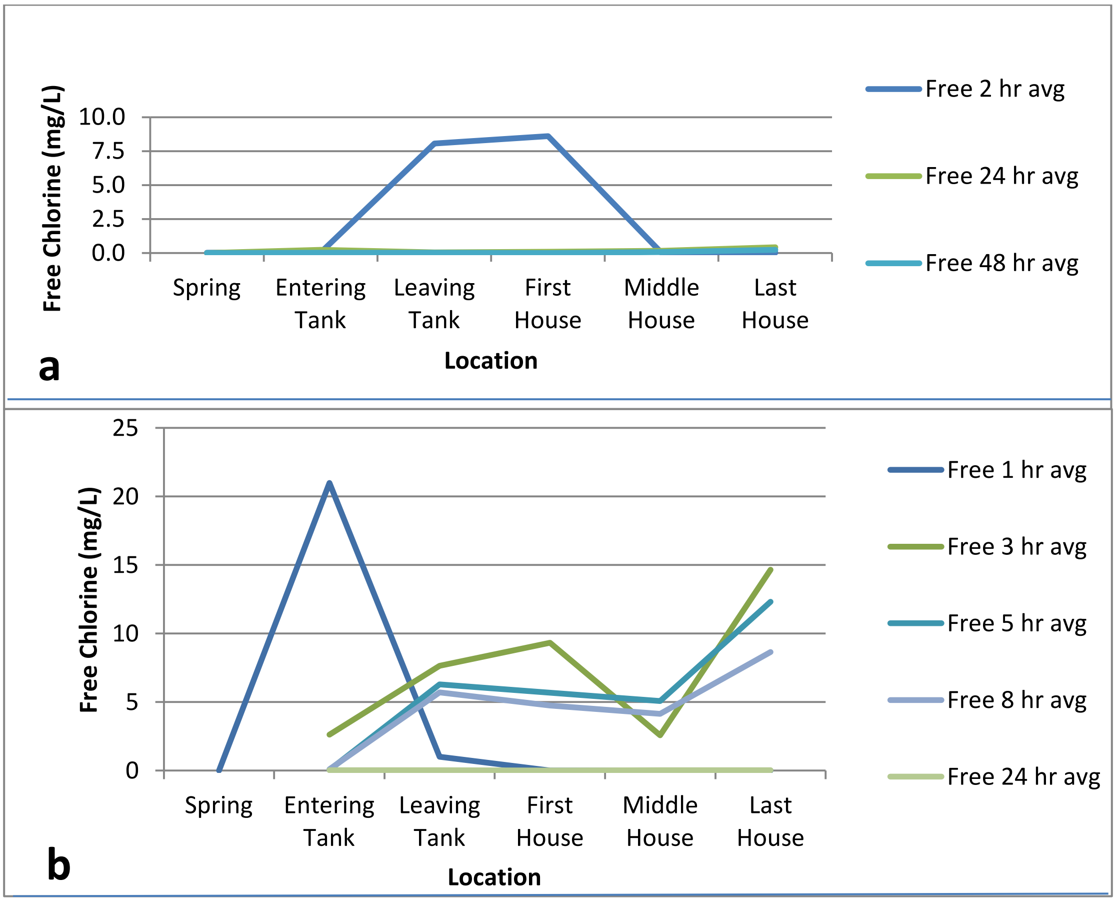

Figure 10: Free Chlorine Concentration Measured in Quebrada Mina Water System at Different Locations during Field Study 1 (April 28-30, 2011) and Field Study 2 (June 17-20, 2011). Results are shown for different time periods after the addition of one chlorine tablet that was not provided in a sealed plastic wrapper.
a) Field Study 1 (April 28-30, 2011)
b) Field Study 2 (June 17-20, 2011)

Table 14: Free Chlorine Concentration Measured in Quebrada Mina Water System at Different Locations during Field Study 1 (April 28-30, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 2 hr	Free Chlorine (mg/L) at 24 hr	Free Chlorine (mg/L) at 48 hr
Spring	0.02	0.01	0.01
Entering Tank	0.05	0.24	0.03
Leaving Tank	8.05	0.06	0.04
First House	8.60	0.11	0.01
Middle House	0.02	0.18	0.08
Last House	0.02	0.42	0.25

Table 15: Free Chlorine Concentration Measured in Quebrada Mina Water System at Different Locations during Field Study 2 (June 17-20, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 1 hr	Free Chlorine (mg/L) at 3 hr	Free Chlorine (mg/L) at 5 hr	Free Chlorine (mg/L) at 8 hr	Free Chlorine (mg/L) at 24 hr
Spring	0.00				
Entering Tank	21.0	2.6	0.05	0.10	0.03
Leaving Tank	1.02	7.7	6.3	5.7	0.04
First House	0.00	9.3	5.7	4.8	0.01
Middle House	0.00	2.6	5.1	4.2	0.04
Last House	0.00	14.7	12.3	8.7	0.04

In Field Study 1 in Calabazal, shown in Figure 11a, free chlorine concentrations above 8 mg/L were recorded at 2 hours leaving the tank, at the middle house, and at the last house. The values decreased to a maximum free chlorine concentration of 0.14 mg/L after 24 hours and 0.01 mg/L after 48 hours.

Free chlorine concentrations during Field Study 2, shown in Figure 11b, at the houses increased from 0.59-2.01 mg/L after 1 hour to 1.50-2.9 mg/L after 3 hours and then decreased to 0.10-0.39 mg/L after 5 hours and remained steady at 0.05-0.36 mg/L after 8 hours. Because of darkness and safety concerns, further testing was not conducted after 8 hours. Water continued to flow out of two overflow pipes and out the tank breather throughout the field testing due to an abundance of water entering the tank and low demand, possibly losing some chlorinated water. Because future water system operators will work to maintain chlorine concentration in the system at all times, results from Field Studies 1-2 indicate that tablets should be replaced daily to maintain proper free chlorine concentration in the system at all times. To mimic that situation, Field Study 4 commenced the day immediately after the chlorine concentration left the system from Field Study 3.

In Field Study 3, shown in Figure 11c, free chlorine concentration entering the tank dropped from 4.6 mg/L after 1 hour to 0.08 mg/L after 3 hours, indicating that the tablet dissolved rapidly. The maximum free chlorine concentration recorded at the houses dropped from 2.8 mg/L (1 hour) to 1.44 mg/L (3 hours) to 0.38 mg/L (5 hours) to 0.18 mg/L (8 hours) to 0.03 mg/L (23 hours). Field Study 4 indicated similar results, with maximum free chlorine dropped from 3.2 mg/L (1 hour) to 1.93 mg/L (3 hours) to 1.15 mg/L (5 hours) 0.60 mg/L (8 hours) to 0.05 mg/L (23 hours). The slightly higher values between Field Studies 3 and 4 indicate that chlorine demand possibly increased when chlorine was not present. One possible explanation for the slightly higher values further away from the storage tank in Field Study 4 could be from the chlorine tablet breaking apart into smaller pieces and dissolving as they move downstream. The higher values also could be from the initial shock of the dissolving chlorine tablet moving downstream, being filled in by unchlorinated water upstream. Field Studies 1-4 all show the tablet dissolving within three hours, with free chlorine concentrations falling below 0.5 mg/L within 8 hours.

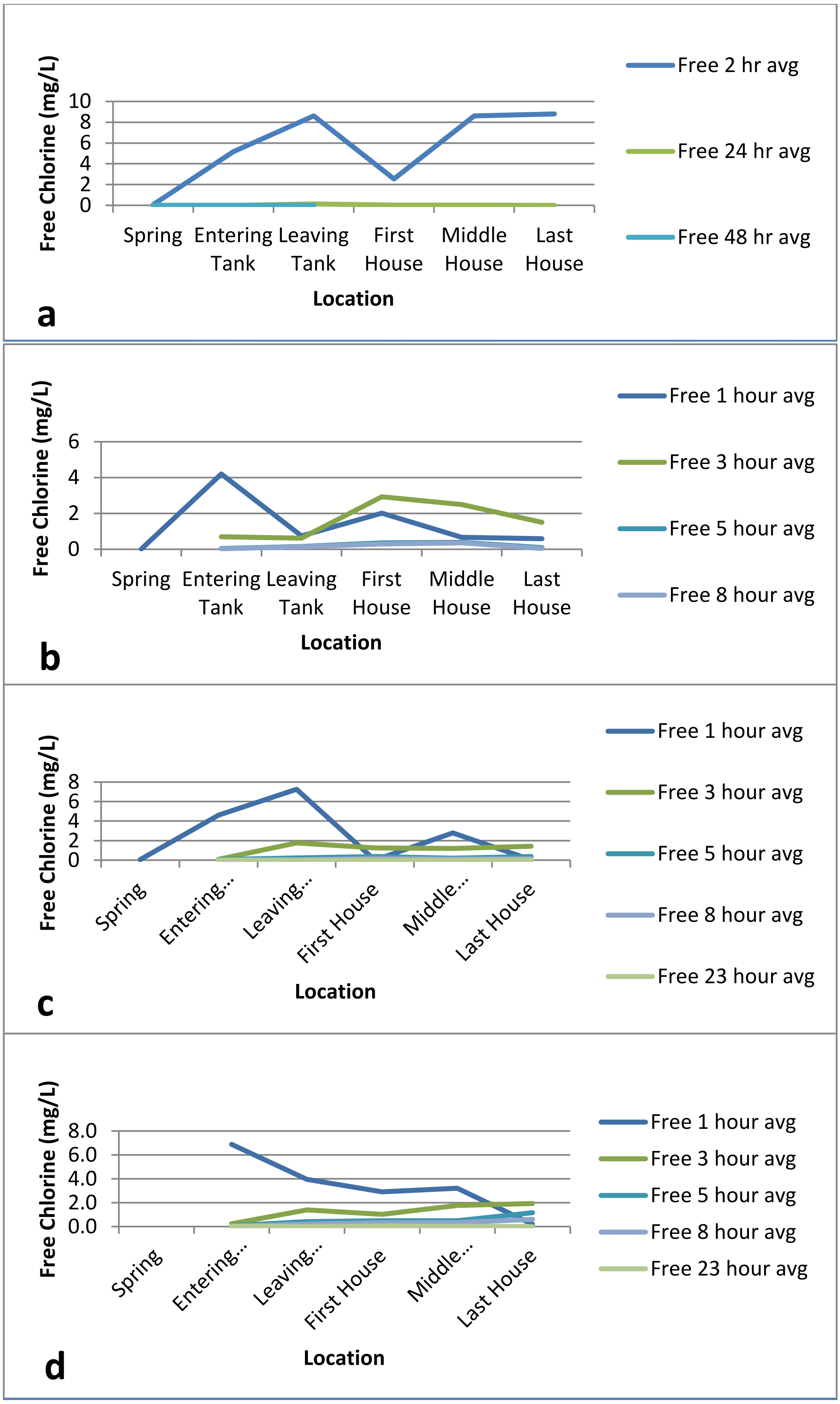

Figure 11: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 1 (April 28-30, 2011), Field Study 2 (June 17-20, 2011), Field Study 3 (June 22-23, 2011), and Field Study 4 (June 23-24, 2011). Results are shown for different time periods after the addition of one chlorine tablet that was not provided in a sealed plastic wrapper. a) Field Study 1 (April 28-30, 2011) b) Field Study 2 (June 17-20, 2011) c) Field Study 3 (June 22-23, 2011) d) Field Study 4 (June 23-24, 2011)

Table 16: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 1 (April 28-30, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 2 hr	Free Chlorine (mg/L) at 24 hr	Free Chlorine (mg/L) at 48 hr
Spring	0.07	0.01	0.01
Entering Tank	5.2	0.01	0.01
Leaving Tank	8.6	0.14	0.01
First House	2.6	0.04	
Middle House	8.6	0.03	
Last House	8.8	0.02	

Table 17: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 2 (June 17-20, 2011). Results are shown for different time periods afterinsertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 1 hr	Free Chlorine (mg/L) at 3 hr	Free Chlorine (mg/L) at 5 hr	Free Chlorine (mg/L) at 8 hr
Spring	0.02			
Entering Tank	4.2	0.69	0.04	0.03
Leaving Tank	0.74	0.62	0.15	0.14
First House	2.0	2.9	0.36	0.29
Middle House	0.67	2.50	0.39	0.36
Last House	0.59	1.50	0.10	0.05

Table 18: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 3 (June 22-23, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 1 hr	Free Chlorine (mg/L) at 3 hr	Free Chlorine (mg/L) at 5 hr	Free Chlorine (mg/L) at 8 hr	Free Chlorine (mg/L) at 23 hr
Spring	0.07				
Entering Tank	4.6	0.08	0.06	0.04	0.02
Leaving Tank	7.3	1.77	0.24	0.04	0.02
First House	0.00	1.26	0.37	0.18	0.00
Middle House	2.8	1.21	0.22	0.13	0.02
Last House	0.03	1.44	0.38	0.15	0.03

Table 19: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 4 (June 23-24, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 1 hr	Free Chlorine (mg/L) at 3 hr	Free Chlorine (mg/L) at 5 hr	Free Chlorine (mg/L) at 8 hr	Free Chlorine (mg/L) at 23 hr
Entering Tank	6.9	0.22	0.05	0.03	0.04
Leaving Tank	4.0	1.38	0.42	0.20	0.00
First House	2.9	1.01	0.47	0.33	0.05
Middle House	3.2	1.77	0.49	0.33	0.03
Last House	0.2	1.93	1.15	0.60	0.00

Results of Free Chlorine Concentration Measured in the Calabazal Water System Using One Tablet Installed in the Chlorinator that was Stored in the Sealed Plastic Wrapper before Use

The free chlorine concentration for Calabazal, tested for in Field Studies 5 and 6, used one tablet stored in a sealed plastic wrapper before use. The results are displayed in Figures 12a-b and Tables 20-21.

In Field Study 5, one tablet, which was stored in a sealed plastic wrapper before use, reported consistent values of 0.02-0.24 mg/L free chlorine in days 1-6, steadily declining over time. The 2 hour free chlorine concentration entering the tank was higher (0.36 mg/L) and at day 7 was lower (0.01 mg/L) than day 1-day 6. The maximum free chlorine concentration decreases throughout the test from 0.24 mg/L (day 1) to 0.14 mg/L (day 4) to 0.04 mg/L (day 7). Field Study 6 was similar, reporting free chlorine concentration of 0.04-0.24 mg/L during days 1-6 and falling below 0.02 mg/L on day 7.

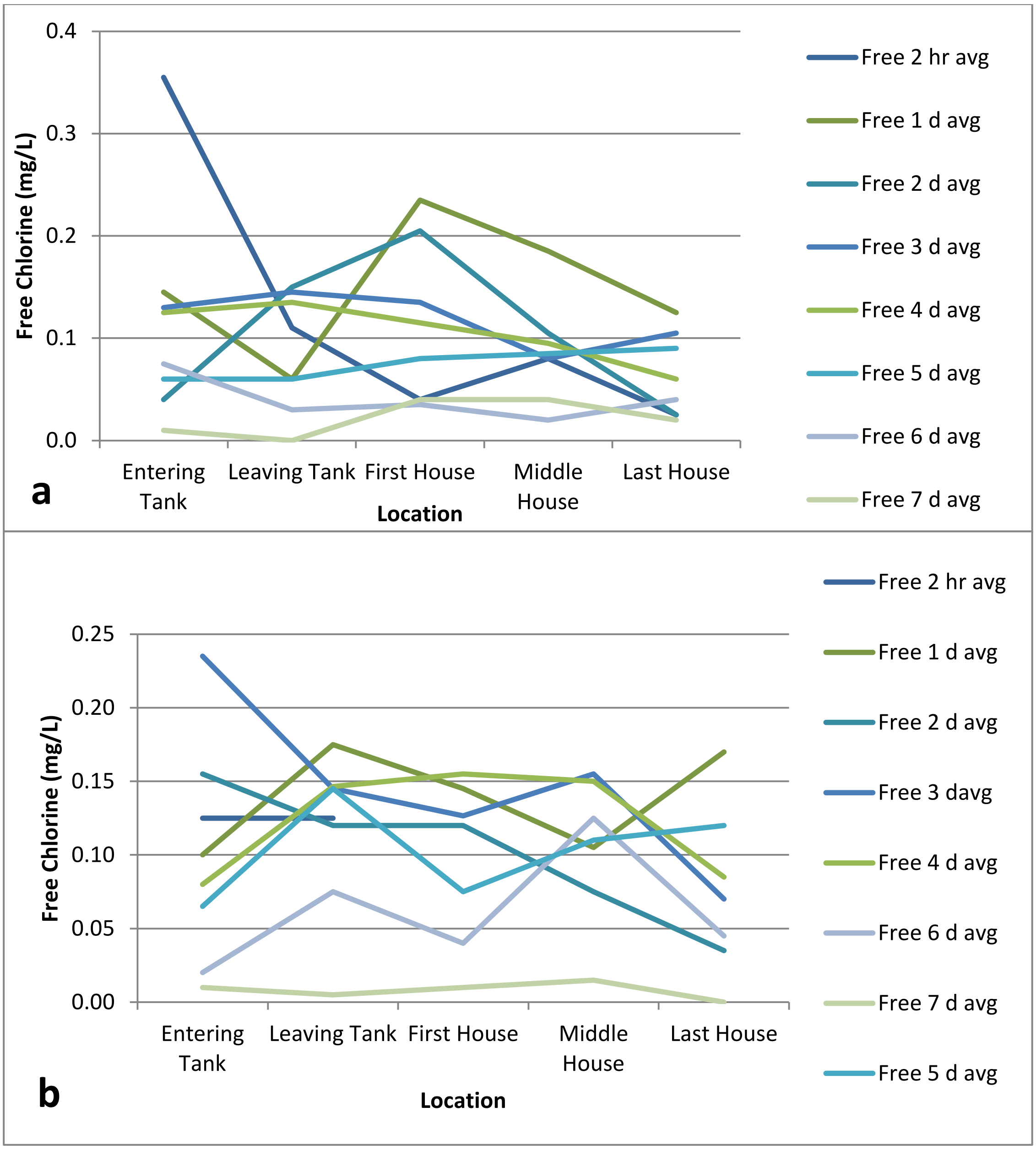

Figure 12: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 5 (August 7-14, 2011) and Field Study 6 (August 17-24, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was stored in a sealed plastic wrapper. a) Field Study 5 (August 7-14, 2011) b) Field Study 6 (August 17-24, 2011)

Table 20: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 5 (August 7-14, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was stored in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 2 hr	Free Chlorine (mg/L) at 1 d	Free Chlorine (mg/L) at 2 d	Free Chlorine (mg/L) at 3 d	Free Chlorine (mg/L) at 4 d	Free Chlorine (mg/L) at 5 d	Free Chlorine (mg/L) at 6 d	Free Chlorine (mg/L) at 7 d
Entering Tank	0.36	0.15	0.04	0.13	0.13	0.06	0.08	0.01
Leaving Tank	0.11	0.06	0.15	0.15	0.14	0.06	0.03	0.00
First House	0.04	0.24	0.21	0.14	0.12	0.08	0.04	0.04
Middle House	0.08	0.19	0.11	0.08	0.10	0.09	0.02	0.04
Last House	0.03	0.13	0.03	0.11	0.06	0.09	0.04	0.02

Table 21: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 6 (August 17-24, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was stored in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 2 hr	Free Chlorine (mg/L) at 1 d	Free Chlorine (mg/L) at 2 d	Free Chlorine (mg/L) at 3 d	Free Chlorine (mg/L) at 4 d	Free Chlorine (mg/L) at 5 d	Free Chlorine (mg/L) at 6 d	Free Chlorine (mg/L) at 7 d
Entering Tank	0.13	0.10	0.16	0.24	0.08	0.07	0.02	0.01
Leaving Tank	0.13	0.18	0.12	0.15	0.15	0.15	0.08	0.01
First House		0.15	0.12	0.13	0.16	0.08	0.04	0.01
Middle House		0.11	0.08	0.16	0.15	0.11	0.13	0.02
Last House		0.17	0.04	0.07	0.09	0.12	0.05	0.00

Results of Free Chlorine Concentration Measured in the Calabazal Water System Using Three Tablets Installed in the Chlorinator that were Stored in the Plastic Wrapper before Use

Values from Field Studies 5 and 6 remained below the recommended value of 0.3 mg/L for inactivation of pathogens present in Panama. In an effort to increase the free chlorine concentration above 0.3 mg/L, three tablets stored in wrapper before use were inserted in the chlorinator and their results displayed in Table 22 and Figure 13.

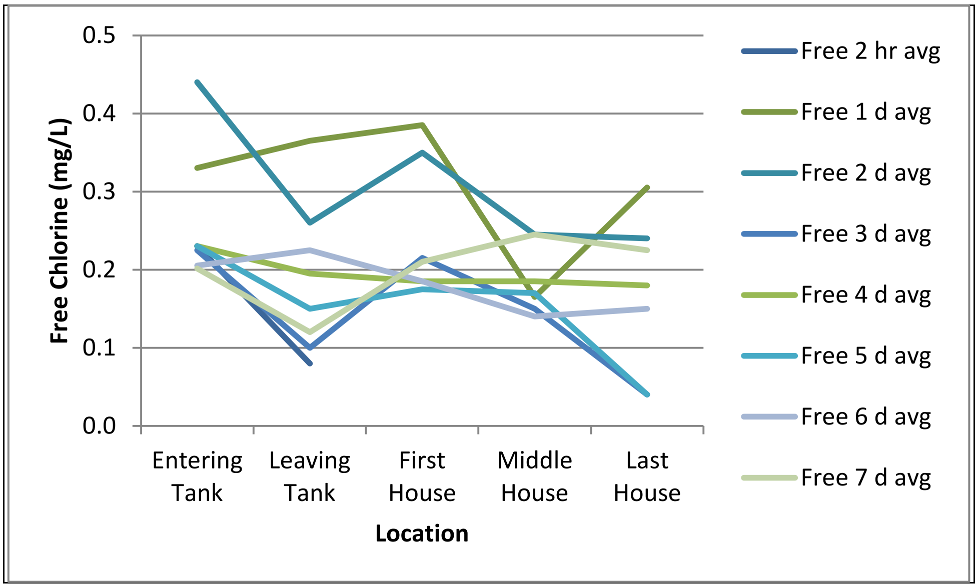

Figure 13: Calabazal Three Tablets Stored in Wrapper before Use Field Study 7 Free Chlorine and Total Chlorine Concentration

Table 22: Free Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 7 (August 25-September 1, 2011). Results are shown for different time periods after insertion of three chlorine tablets that were stored in a sealed plastic wrapper.

Location	Free Chlorine (mg/L) at 2 hr	Free Chlorine (mg/L) at 1 d	Free Chlorine (mg/L) at 2 d	Free Chlorine (mg/L) at 3 d	Free Chlorine (mg/L) at 4 d	Free Chlorine (mg/L) at 5 d	Free Chlorine (mg/L) at 6 d	Free Chlorine (mg/L) at 7 d
Entering Tank	0.23	0.33	0.44	0.23	0.23	0.23	0.21	0.20
Leaving Tank	0.08	0.37	0.26	0.10	0.20	0.15	0.23	0.12
First House		0.39	0.35	0.22	0.19	0.18	0.19	0.21
Middle House		0.17	0.25	0.15	0.19	0.17	0.14	0.25
Last House		0.31	0.24	0.04	0.18	0.04	0.15	0.23

With the exception of days 1 and 2, when the values increase up to 0.44 mg/L, the free chlorine concentration entering the tank remained constant between 0.20 and 0.23 mg/L. All other values congregated between 0.15 and 0.35 mg/L through the testing, trending slightly downward with time.

Acknowledging the deficiencies of one tablet without wrapper, Figure 14 and Table 23 compare one tablet stored in sealed plastic wrapper before use (Field Studies 5 and 6) and three tablets stored in sealed plastic wrapper before use (Field Study 7). Free chlorine leaving the tank is compared because that value will be used as C in the Ct method.

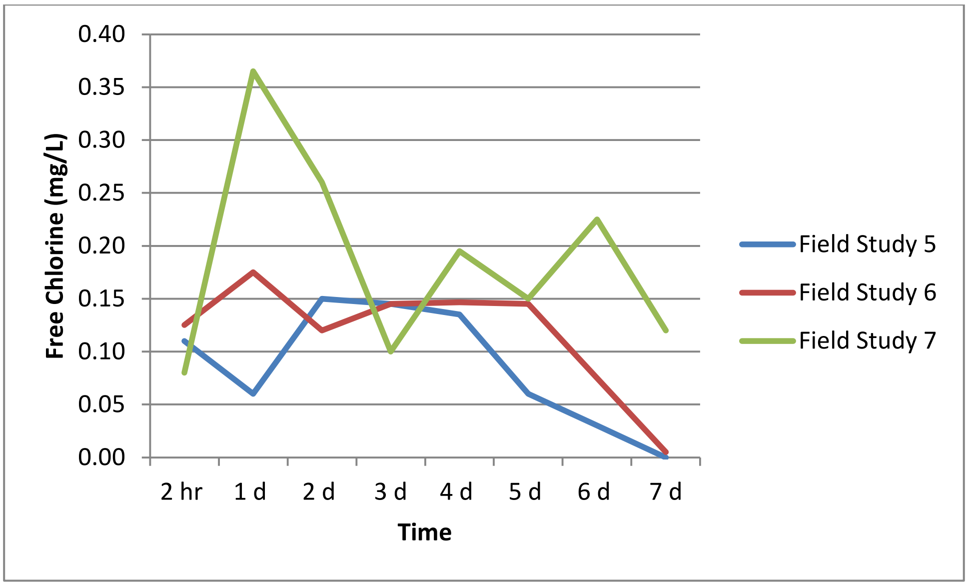

Figure 14: Free Chlorine Concentration Measured in Calabazal Water System Leaving Tank during Field Studies 5, 6, and 7. Results are shown for different time periods after insertion of one tablet stored in sealed plastic wrapper before use (Field Studies 5 and 6) and three tablets stored in sealed plastic wrapper before use (Field Study 7).

Table 23: Free Chlorine Concentration Measured in Calabazal Water System Leaving Tank during Field Studies 5, 6, and 7. Results are shown for different time periods after insertion of one tablet stored in sealed plastic wrapper before use (Field Studies 5 and 6) and three tablets stored in sealed plastic wrapper before use (Field Study 7).

# Tablets	Free Chlorine (mg/L) at 2 hr	Free Chlorine (mg/L) at 1 d	Free Chlorine (mg/L) at 2 d	Free Chlorine (mg/L) at 3 d	Free Chlorine (mg/L) at 4 d	Free Chlorine (mg/L) at 5 d	Free Chlorine (mg/L) at 6 d	Free Chlorine (mg/L) at 7 d
1 Tablet (Field Study 5)	0.11	0.06	0.15	0.15	0.14	0.06	0.03	0.00
1 Tablet (Field Study 6)	0.13	0.18	0.12	0.15	0.15	0.15	0.08	0.01
3 Tablets (Field Study 7)	0.08	0.37	0.26	0.10	0.20	0.15	0.23	0.12

The Ct values determined during field testing will be compared to Ct requirements defined by various organizations and also by Ct requirements for the inactivation of pathogens specific to Panama. Table 24 summarizes the Ct and concentration requirements by various regulatory and public health organizations.

WHO recommends no more than 5.0 mg/L free chlorine concentration and CDC recommends no more than 2.0 mg/L, so that no unpleasant taste or odor is found. The Ct required for pathogens is also noted in Table 25 for pathogens common to Panama, including *Salmonella typhi*, Hepatitis A, *Giardia lamblia*, *E. coli*, and *E. Hystolytica*, and other pathogens of interest to the global health community such as *Vibrio cholerae* and Rotavirus.

Table 24: Ct or Concentration Requirements as defined by Various Regulatory and Public Health Organizations

Organization	Ct Requirement (mg*min/L)	Concentration Requirement (mg/L)
Surface Water Treatment Rule		0.2
EPA (2 log removal)	50	
Wisconsin DNR		0.5
Center for Disease Control (in terms of storage)		0.2 (after 24 hours of storage)
Connecticut Department of Public Health	2	0.2 (for 10 minutes)
Connecticut Department of Public Health (4 log removal)	6	
WHO (bacteria)	0.04-0.08	
WHO (viruses)	2-30	
WHO (protozoa)	25-245	
Parr, et al.		0.3-0.5

(EPA, 2011; Wisconsin DNR, 2007; Center for Disease Control, 2011; State of Connecticut Department of Public Health, 2010; WHO, 2011; Parr, et al., 1995)

Table 25: Ct Required Using Chlorination for Inactivation of Pathogens Common to Panama and Pathogens Common in Cases of Intervention. Ct values valid at temperature and pH listed in the table. (Center for Disease Control, 2007)

Pathogen	**Ct Required for Pathogen Inactivation (mg x min/L)**	**Temperature C**	**pH**
Salmonella typhi	1	20-25	7
Hepatitis A	0.41	25	8
Giardia lamblia	15	25	7
E. coli	0.25	23	7
E. Hystolytica	20	27-30	7
Vibrio cholerae	0.5	20	7
Rotavirus	0.05	4	7

Of the organizations listed, WHO has the highest Ct standard among those focused in the developing world (Table 24) at 25 mg x min/L for the inactivation of most bacteria, viruses, and protozoa. Of the Ct requirements to inactivate common pathogens in Panama, *E. hystolytica* has the highest Ct requirement of 20 mg*min/L. Some organizations in the United States, like the EPA and the Connecticut Department of Public Health, require the Ct value to be met before or at the first house on the transmission line. This study used the concentration leaving the storage tank because of its close proximity to the first house and to the rest of the system, the additional contact time of chlorine in the water, and because the operator would be at the storage tank to operate and maintain the chlorinator, located two meters up line from the storage tank.

A schematic of the storage tank in Calabazal is shown in Figure 15. The water from the spring passes through the chlorinator before entering the tank from the top left hand side of the figure. The chlorinated water leaves both through the outflow but also the overflow, wasting chlorinated water, because of the large inflow of water into the storage tank.

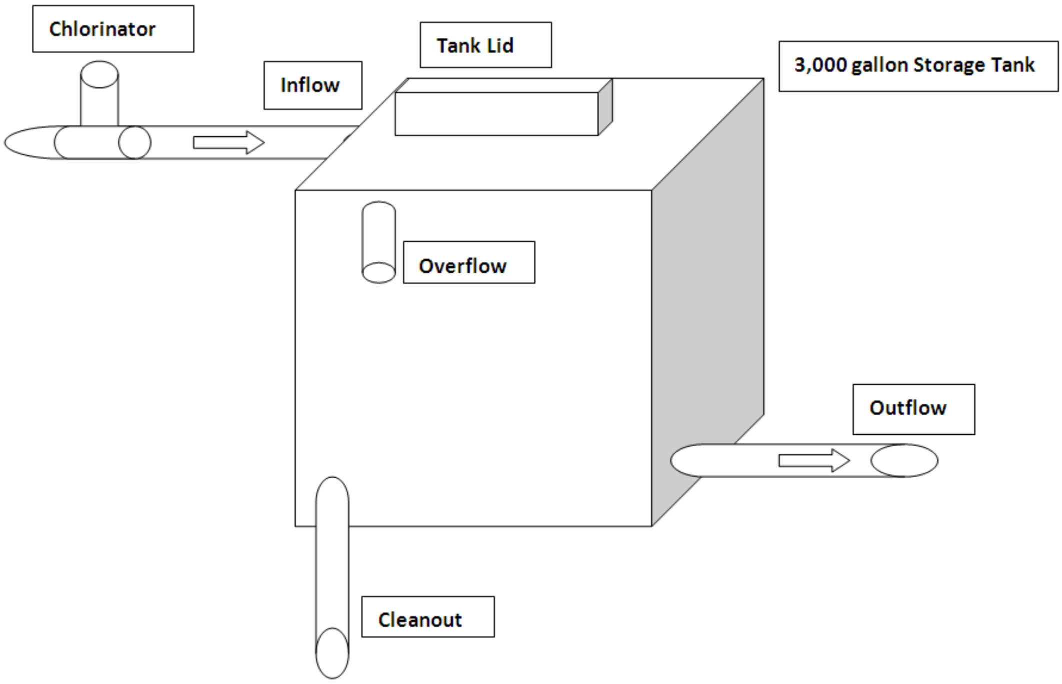

Figure 15: Diagram of 3,000-Gallon Storage Tank in Calabazal. The water from the spring passes through the chlorinator, enters the tank on the top left, and leaves the tank on the bottom right. Water continuously leaves the tank through the overflow.

To compare field Ct values to Ct values obtained from literature (provided in Tables 24 and 25), concentration and time are needed, where C (mg/L) is the free chlorine concentration leaving the tank (assuming water in the tank is completely mixed in the tank) and t is the residence time of the storage tank (minutes). The field free chlorine concentration values leaving the tank are found in Table 23. In Calabazal, the tank volume is 3,000 gallons (11,350 liters). The maximum flow recorded over the course of this study was 15.9 gallons per minute (60 liters per minute).

If the tank was completely mixed, the contact time would simply be the volume divided by the flow. However, if the inlet and outlet are unbaffled and there are no intrabasin baffles, the baffling condition is considered poor. In such cases a baffling factor of 0.3 is used because the poor circulation causes reduced contact time (State of Connecticut Department of Public Health, 2010). Therefore, estimated contact time in the tank is 56.6 minutes (3,000 gallons /15.9 gpm×0.3). If the baffling factor was ignored, the contact time in the tank would increase to 189 minutes, in which case the required concentration would drastically decrease. In order to reach a conservative answer in which it is more likely that pathogens are inactivated, the baffling factor of 0.3 was used.   In Table 26, the pathogens common to Panama and their respective Ct values are compared to the free chlorine concentration and residence time measured during field testing.

According to the values calculated during this study, one tablet stored in a wrapper before use between 2 hours and 6 days was not able to inactivate *Giardia lamblia* and *E. hystolytica*. Three tablets stored in a wrapper before use was only able to inactivate *Giardia lamblia* and *E. hystolytica* on day 1. Both scenarios were able to inactivate all other pathogens common to Panama, as well as *vibrio cholerae* and rotavirus, pathogens of interest to the global health community. Both scenarios indicated concentrations falling below the required concentration to inactivate pathogens after seven full days of the tablet being in the system, therefore a new tablet should be inserted on a weekly basis.

Table 26: Comparison of Ct and Free Chlorine Concentration Required for Pathogen Inactivation for Pathogens Present in Panama to Free Chlorine Concentration Measured in Calabazal Water System Leaving Tank during Field Studies 5,6, and 7. Results are shown for different time periods after insertion of one tablet stored in sealed plastic wrapper before use (Field Studies 5 and 6) and three tablets stored in sealed plastic wrapper before use (Field Study 7).
a) One Tablet (Field Study 5) b) One Tablet (Field Study 6) c) Three Tablets (Field Study 7)

a)											
Pathogen	Ct Required for Pathogen Inactivation (mg/L/min)	Time (min)	Free Chlorine Concentration Required for Pathogen Inactivation (mg/L)	2 hr	1 d	2 d	3 d	4 d	5 d	6 d	7 d
Salmonella typhi	1	56.6	0.02	+	+	+	+	+	+	+	-
Hepatitis A	0.41	56.6	0.01	+	+	+	+	+	+	+	-
Giardia lamblia	15	56.6	0.27	-	-	-	-	-	-	-	-
E. coli	0.25	56.6	0.00	+	+	+	+	+	+	+	-
E. Hystolytica	20	56.6	0.35	-	-	-	-	-	-	-	-
Vibrio cholerae	0.5	56.6	0.01	+	+	+	+	+	+	+	-
Rotavirus	0.05	56.6	0.00	+	+	+	+	+	+	+	-

"+" indicates that the field free chlorine concentration exceeds the required concentration for pathogen inactivation.
"-" indicates that the field free chlorine concentration does not exceed the required concentration for pathogen inactivation.

Table 26 (continued)

b)

Pathogen	Ct Required for Pathogen Inactivation (mg/L/min)	Time (min)	Concentration Required for Pathogen Inactivation (mg/L)	2 hr	1 d	2 d	3 d	4 d	5 d	6 d	7 d
Salmonella typhi	1	56.6	0.02	+	+	+	+	+	+	+	-
Hepatitis A	0.41	56.6	0.01	+	+	+	+	+	+	+	+
Giardia lamblia	15	56.6	0.27	-	-	-	-	-	-	-	-
E. coli	0.25	56.6	0.00	+	+	+	+	+	+	+	+
E. Hystolytica	20	56.6	0.35	-	-	-	-	-	-	-	-
Vibrio cholerae	0.5	56.6	0.01	+	+	+	+	+	+	+	+
Rotavirus	0.05	56.6	0.00	+	+	+	+	+	+	+	+

"+" indicates that the field free chlorine concentration exceeds the required concentration for pathogen inactivation.
"-" indicates that the field free chlorine concentration does not exceed the required concentration for pathogen inactivation

c)

Pathogen	Ct Required for Pathogen Inactivation (mg/L/min)	Time (min)	Concentration Required for Pathogen Inactivation (mg/L)	2 hr	1 d	2 d	3 d	4 d	5 d	6 d	7 d
Salmonella typhi	1	56.6	0.02	+	+	+	+	+	+	+	+
Hepatitis A	0.41	56.6	0.01	+	+	+	+	+	+	+	+
Giardia lamblia	15	56.6	0.27	-	+	-	-	-	-	-	-
E. coli	0.25	56.6	0.00	+	+	+	+	+	+	+	+
E. Hystolytica	20	56.6	0.35	-	+	-	-	-	-	-	-
Vibrio cholerae	0.5	56.6	0.01	+	+	+	+	+	+	+	+
Rotavirus	0.05	56.6	0.00	+	+	+	+	+	+	+	+

"+"indicates that the field free chlorine concentration exceeds the required concentration for pathogen inactivation.
"-" indicates that the field free chlorine concentration does not exceed the required concentration for pathogen inactivation

Chapter 5: Conclusions and Recommendations for Future Research and Field Application

Water quality is directly linked to health, noted extensively in many peer reviewed reports. In-line chlorination is one technology that can be used in a rural gravity flow water system found in the developing world to inactivate pathogens and improve water quality. The purpose of this study was to determine the effectiveness of the Panamanian Ministry of Health's in-line PVC chlorinator. To do so, free chlorine concentration was measured entering the storage tank, leaving the storage tank, and at three households along the transmission line of the water system in the two rural indigenous communities of Calabazal and Quebrada Mina in western Panama.

The study's hypotheses investigated the immediate effects of the insertion of a new tablet on chlorine concentration in the system, the effect of distance on chlorine concentration, the effect of flow on chlorine concentration, and the comparison of established Ct values with actual Ct values determined from field measurements of chlorine concentration and contact time.

Measuring the chlorine concentration in the system, both immediately after a new tablet was added to an in-line chlorinator and after more time had elapsed, showed higher free chlorine concentration immediately after insertion of a new tablet. Field Studies 1-4 note that an unsealed tablet in a plastic wrapper before use dissolves in approximately three hours. Therefore, an unsealed tablet can cause the chlorine to dissolve at a faster rate than normal. Field Studies 5 and 6 recorded the results using one tablet from a sealed plastic wrapper. Field Study 5 entering the tank indicates a concentration of 0.36 mg/L that reduces to 0.15 mg/L after 1 day. Values at the houses on the transmission line in Field Study 5 decreased from 0.13-0.24 mg/L after 1 day to 0.08-0.14 mg/L after 3 days, dissolving approximately 30 grams of the tablet per day instead of approximately 45 grams of the tablet. Field Study 6 displays constant values of free chlorine concentration both entering the tank (0.13 mg/L after 2 hours, 0.10 mg/L after 1 day, 0.17 mg/L after 2 days) as well as at the houses (0.11-0.17 mg/L after 1 day, 0.07-0.16 mg/L after 3 days). Field Study 7, when three tablets were inserted, results in a slow increase in concentration entering the tank from 2 hours (0.23 mg/L) to day 2 (0.44 mg/L) before decreasing during the rest of the testing period. The residual at the houses shows the same trend as the previous rounds, decreasing slowly over the time from day 1 (0.17-0.39 mg/L) to day 3 (0.04-0.22 mg/L).

The second hypothesis relates free chlorine concentration to distance from the in-line chlorinator. In Calabazal, the distance from the tank to the last house on the line is less than 350 meters, a lot shorter than transmission lines in other rural communities throughout the world. Measuring the chlorine residual at faucets located at various intervals from the chlorinator gave very little change between leaving the tank and the last house on the line, indicating little chlorine demand added in the transmission line leaving the tank. In Field Study 5, of the eight time intervals of testing, four decreased in concentration and four increased in concentration from leaving the tank to the last house on the transmission line. Field Study 6 reported all concentrations decreasing from the tank to the last house. Field Study 7 also reported all concentrations decreasing from the tank to the last house, with the exception of day 7, the last day of testing. This indicates that free chlorine concentration decreases as distance from the tank increases.

Measuring the weight loss of the chlorine tablet in association with the flow, more weight loss of the tablet occurred with greater flow in to the tank (Appendix C). Reflecting on the data from the insertion of one tablet, not sealed in a plastic wrapper before use, indicates that in Quebrada Mina the flow increased by a factor of fifteen between Field Study 1 and Field Study 2 (0.21 to 3.18 gpm), however this was not reflected in tablet weight loss which decreased from 120 g over one hour in Field Study 1 and 138 grams in one hour in Field Study 2. Likewise, the flow entering the tank in Calabazal increased by a factor of three from Field Study 1 to Field Studies 2-4, however the difference in tablet weight was inconsequential. The tank was full of water throughout the field studies and the flow rate remained constant into the tank, therefore the residence time was not affected. The results of tablet weight and flow entering the tank report that the tablet weight and flow were not correlated. However, the claimed duration of the tablet, based on the manufacturer’s claim that 2 g of the tablet will dissolve in every 1,000 liters of flow, was greatly overestimated for the tablets left unsealed prior to use, whereas the tablets sealed prior to use dissolved 0.34 g of the tablet in every 1,000 liters of flow (Appendix C).

Based on a list of pathogens common in Panama and pathogens of interest to the global health community and their respective Ct values from the literature, the required concentration for pathogen inactivation was compared to field values of free chlorine concentration. The Ct values are based on disinfection using free chlorine because Ct is a function of the disinfectant. The free chlorine concentration was compared using the Ct method to the concentration required to inactivate common pathogens found in gravity flow water systems in Panama, such as *E. coli*, *Salmonella typhi*, Hepatitis A, *Giardia lamblia*, and *E. histolytica,* and other pathogens of interest to the global health community, such as *Vibrio cholerae* and Rotavirus. Chlorine tablets sealed in a plastic wrapper reduced contact with humid surroundings prior to use, and this extended the dissolution time and increased the time in the transmission line. One tablet sealed in a plastic wrapper before use achieved the required free chlorine concentration to disinfect *E. coli*, *Vibrio cholerae*, Rotavirus, *Salmonella typhi*, and Hepatitis A, but achieved neither the 0.27 mg/L needed to inactivate *Giardia lamblia* nor the 0.35 mg/L needed to inactivate *E. histolytica*. The use of three tablets was able to provide free chlorine concentration above 0.35 mg/L for only one day, reaching 0.37 mg/L, before falling below 0.35 mg/L to a level of 0.26 mg/L the next day. Results indicated that one tablet was able to inactivate most pathogens; however three tablets reached slightly higher free chlorine concentration. Given a 3,000 gallon tank and 15.90 gallons per minute of flow, 0.35 mg/L of free chlorine is required leaving the tank to disinfect all pathogens. Design and operation are based on the flow through the chlorinator, therefore the required concentration will be different in communities with a different flow rate.

Future research should be performed in the field on additional scenarios using the PVC in-line chlorinator. For example, variations in flow, size, and location of the inlet hole into the chlorinator could be tested to achieve the required free chlorine concentration for pathogen inactivation. Different types of calcium hypochlorite tablets could be tested—they could potentially have different inert materials that could affect the rate of dissolution into the water. One and three tablets were used in this study—other quantities of tablets could be used in future studies. Additionally, various regions have different pathogens common to their particular area, as well as varying temperature, turbidity, and pH. Reactions speed increases with increased temperature, whereas turbidity could negatively impact the ability of chlorine to react with pathogens in the water. If the turbidity is high, tanks could be put in series to allow both settling of particles and sufficient residence time. pH also affects the balance of HOCl and OCl^-, with optimum conditions above 7.6 so that HOCl is preferred in solution . The effects of temperature, turbidity, and pH could all be studied in relation to the PVC in-line chlorinator, therefore testing of the in-line chlorinator in other parts of the developing world would be beneficial.

Additionally, future research could be done on the implementation of an in-line chlorinator in an urban setting. The chlorinator can be easily installed into a

PVC line to increase chlorine residual in the transmission line, which could be relavent in long transmission lines. Urban use of the chlorinator could also be necessary during the failure of the existing disinfection system or for intervention in an outbreak of a pathogen such as *vibrio cholerae*.

Very little research exists on the use of modeling in the developing world. The ability to use data easily obtainable in the field for a model of chlorine residual in a water system would be a valuable resource to water system operators across the developing world.

Field implementation would require an initial cost for materials for construction of the chlorinator of approximately $35 USD (year – 2011). The in-chlorinator requires using three $2 tablets a week, therefore the cost of disinfection per month is approximately $24, or approximately $1 per household per month in a community like Calabazal or Quebrada Mina with 25 connections. With the existing tariff of $0.50 per month, the new tariff would increase to $1.50 per month, about 2 percent of household income, somewhat comparable to a US household where income from someone making $8 per hour would have a utility bill of around $30 per month. In the case of Panama, the cost of chlorine tablets is subsidized by the local environmental health agency, but the author recommends including the cost of disinfection to the existing tariff to each household as proper disinfection of the water supply would improve community health, thus reducing the cost of trips to the hospital, doctor's visits, and medicine.

The chlorinator is recommended to be installed upstream from the storage tank to increase contact time, however chlorinated water can be lost if the storage tank is overflowing. The Ministry of Environmental Health in Panama initially distributed the unsealed tablet to the communities in the Comarca Ngabe Bugle. During this time, other Peace Corps Volunteers serving in the region noted the lack of effectiveness of the unsealed tablet and a corresponding lack of confidence from community members of their own water committees. Through communication to the communities they were serving, the Ministry of Environmental Health found out that the unsealed tablet was ineffective and presented individually sealed tablets. Continued communication and interaction with the water committees, especially through visits to the communities themselves, will help ensure correct operation and maintenance of the chlorinator and the water system as a whole. To confirm the correct concentration of chlorine in the water, the Ministry of Health encourages water system operators to use a color wheel, purchased for $15 USD, to visually compare the chlorinated water with a value indicating the amount of chlorine in the water. It is also possible to train members of the community, potentially women, to taste the water to determine whether the amount of chlorine present is below the required level or too high.

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Appendices

Appendix A: In-Line Chlorinator Materials List Developed for Panama

Description	Quantity
4” Cylinder and Screw Cap	1
3” Cylinder and Screw Cap	1
3” Cap	1
4” Union	1
4” Tee	1
4” to 2” Reduction	2
3” Tube	2
4” Tube	2

Appendix B: Total Chlorine Concentration Measurements

Table B.1: Total Chlorine Concentration Measured in Quebrada Mina Water System at Different Locations during Field Study 1 (April 28-30, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	2 hr avg (mg/L)	24 hr avg (mg/L)	48 hr avg (mg/L)
Spring	0.05	0.00	0.04
Entering Tank	8.80	0.45	0.06
Leaving Tank	8.80	0.15	0.11
First House	8.80	0.28	0.04
Middle House	0.00	0.39	0.17
Last House	0.03	0.69	0.34

Table B.2: Total Chlorine Concentration Measured in Quebrada Mina Water System at Different Locations during Field Study 2 (June 17-20, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	1 hr avg (mg/L)	3 hr avg (mg/L)	5 hr avg (mg/L)	8 hr avg (mg/L)	24 hr avg (mg/L)
Spring	0.00				
Entering Tank	27.0	5.1	0.16	0.15	0.16
Leaving Tank	1.01	9.5	8.1	5.9	0.08
First House	0.01	12.5	7.5	4.6	0.10
Middle House	0.02	0.1	6.9	4.4	0.16
Last House	0.00	17.0	16.0	15.0	0.06

Table B.3: Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 1 (April 28-30, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	2 hr avg (mg/L)	24 hr avg (mg/L)	48 hr avg (mg/L)
Spring	0.02	0.01	0.02
Entering Tank	8.80	0.02	0.02
Leaving Tank	8.80	0.26	0.03
First House	7.00	0.04	
Middle House	8.80	0.03	
Last House	8.80	0.02	

Table B.4: Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 2 (June 17-20, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	1 hr avg (mg/L)	3 hr avg (mg/L)	5 hr avg (mg/L)	8 hr avg (mg/L)
Spring	0.02			
Entering Tank	7.80	1.34	0.02	0.05
Leaving Tank	1.23	1.10	1.20	0.16
First House	5.00	5.50	1.51	0.43
Middle House	1.20	4.60	1.34	0.41
Last House	0.77	2.90	0.52	0.15

Appendix B (continued)

Table B.5: Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 3 (June 22-23, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	1 hr avg (mg/L)	3 hr avg (mg/L)	5 hr avg (mg/L)	8 hr avg (mg/L)	23 hr avg (mg/L)
Spring	0.04				
Entering Tank	6.35	0.10	0.12	0.09	0.04
Leaving Tank	7.35	3.30	1.17	0.45	0.01
First House	0.00	2.15	1.09	0.57	0.01
Middle House	3.20	2.20	1.15	0.31	0.02
Last House	0.06	2.50	1.49	0.60	0.04

Table B.6 Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 4 (June 23-24, 2011). Results are shown for different time periods after insertion of one chlorine tablet that was not provided in a sealed plastic wrapper.

Location	1 hr avg (mg/L)	3 hr avg (mg/L)	5 hr avg (mg/L)	8 hr avg (mg/L)	23 hr avg (mg/L)
Entering Tank	7.75	0.40	0.09	0.08	0.00
Leaving Tank	4.20	2.35	1.30	0.63	0.00
First House	3.50	1.55	2.20	0.62	0.05
Middle House	3.90	3.05	1.47	0.66	0.04
Last House	0.22	2.70	1.80	1.71	0.01

Table B.7: Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 5 (August 7-14, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was stored in a sealed plastic wrapper.

Location	2 hr avg (mg/L)	1 d avg (mg/L)	2 d avg (mg/L)	3 d avg (mg/L)	4 d avg (mg/L)	5 d avg (mg/L)	6 d avg (mg/L)	7 d avg (mg/L)
Entering Tank	0.40	0.20	0.09	0.23	0.18	0.10	0.08	0.06
Leaving Tank	0.10	0.14	0.20	0.17	0.17	0.09	0.05	0.00
First House	0.06	0.25	0.26	0.13	0.14	0.08	0.04	0.05
Middle House	0.14	0.21	0.17	0.12	0.15	0.09	0.00	0.01
Last House	0.02	0.18	0.18	0.18	0.15	0.10	0.05	0.04

Table B.8: Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 6 (August 17-24, 2011). Results are shown for different time periods after the insertion of one chlorine tablet that was stored in a sealed plastic wrapper.

Location	2 hr avg (mg/L)	1 d avg (mg/L)	2 d avg (mg/L)	3 d avg (mg/L)	4 d avg (mg/L)	5 d avg (mg/L)	6 d avg (mg/L)	7 d avg (mg/L)
Entering Tank	0.20	0.13	0.15	0.22	0.15	0.04	0.02	0.01
Leaving Tank	0.16	0.25	0.12	0.17	0.20	0.11	0.06	0.06
First House		0.22	0.19	0.14	0.19	0.15	0.11	0.01
Middle House		0.10	0.15	0.21	0.22	0.15	0.11	0.01
Last House		0.16	0.18	0.09	0.12	0.12	0.09	0.01

Appendix B (continued)

Table B.9: Total Chlorine Concentration Measured in Calabazal Water System at Different Locations during Field Study 7 (August 25-September 1, 2011). Results are shown for different time periods after insertion of three chlorine tablets that were stored in a sealed plastic wrapper.

Location	2 hr avg (mg/L)	1 d avg (mg/L)	2 d avg (mg/L)	3 d avg (mg/L)	4 d avg (mg/L)	5 d avg (mg/L)	6 d avg (mg/L)	7 d avg (mg/L)
Entering Tank	0.32	0.43	0.71	0.42	0.28	0.27	0.30	0.31
Leaving Tank	0.07	0.42	0.41	0.27	0.30	0.28	0.32	0.36
First House		0.42	0.46	0.24	0.27	0.26	0.21	0.32
Middle House		0.31	0.42	0.20	0.28	0.22	0.21	0.26
Last House		0.33	0.34	0.15	0.23	0.17	0.29	0.29

Appendix C: Flow and Tablet Weight

Table C.1: Flow Measured in Quebrada Mina and Calabazal Water Systems during Field Studies 1-7

Community	Flow (gpm) in Field Study 1	Flow (gpm) in Field Study 2	Flow (gpm) in Field Study 3-7
Q. Mina (Entrance w/ chlorinator)	0.21	3.18	
Q. Mina (Entrance w/o chlorinator)	0.76	3.97	
Calabazal	5.29	15.90	15.90

Table C.2: Tablet Weights Recorded at Various Time Intervals in Quebrada Mina Water System during Field Studies 1 and 2

Description	Field Study 1	Field Study 2
Dry Weight (g)	196	194
5 min Wet Weight (g)	208	194
1 hr Wet Weight (g)	86	56
24 hr Wet Weight (g)	0	0

Table C.3: Tablet Weights Recorded at Various Time Intervals in Calabazal Water System during Field Studies 1-4

Description	Field Study 1	Field Study 2	Field Study 3	Field Study 4
Dry Weight (g)	193	194	184	186
5 min Wet Weight (g)	204	190	186	186
1 hr Wet Weight (g)		108	66	64
2 hr Wet Weight (g)	12	14		
3 hr Wet Weight (g)			0	0
4 hr Wet Weight (g)		0		
24 hr Wet Weight (g)	0			

Table C.4: Tablet Weights Recorded at Various Time Intervals in Calabazal Water System during Field Studies 5-7

Description	Field Study 5	Field Study 6	Top Tablet in Field Study 7	Middle Tablet in Field Study 7	Bottom Tablet in Field Study 7
Dry Weight (g)	202	198	202	200	200
5 min Wet Weight (g)	206	204	210	208	206
2 hr Wet Weight (g)	208	206	212	212	208
1 day Wet Weight (g)	160	166	200	198	172
2 day Wet Weight (g)	114	130	172	178	130
3 day Wet Weight (g)	76	92	154	166	102
4 day Wet Weight (g)	46	62	140	154	80
5 day Wet Weight (g)	12	36	124	140	58
6 day Wet Weight (g)	4	14	106	126	30
7 day Wet Weight (g)	0	2	90	98	2

Appendix C (continued)

Table C.5: Comparison of Actual Duration of Chlorine Tablet against Claimed Duration of Tablet based on Manufacturer's Claim of 2g of Chlorine for Every 1000 Liters of Water Passing through Chlorinator in Field Studies 1-7 in the Communities of Quebrada Mina and Calabazal

Community	Field Study	Flow (gpm)	Flow (Lpm)	Duration of Tablet (d)	Volume of flow over tablet (L)	Starting Weight (g)	Rate of Dissolution (g/1000 L)
Q. Mina	1	0.21	0.79	0.1	114	208	1820
Q. Mina	2	3.18	12.04	0.1	1733	194	112
Calabazal	1	5.29	20.02	0.1	2883	204	70.8
Calabazal	2	15.9	60.18	0.1	8666	190	21.9
Calabazal	3	15.9	60.18	0.1	8666	186	21.5
Calabazal	4	15.9	60.18	0.1	8666	186	21.5
Calabazal	5	15.9	60.18	7	606630	206	0.34
Calabazal	6	15.9	60.18	7	606630	204	0.34
Calabazal	7	15.9	60.18	7	606630	206	0.34