

Research Paper

Pipe enlargement to satisfy concentration-time product for in-system disinfection in a water distribution system

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ABSTRACT

C^*t is used as a metric for disinfection in a water treatment plant while inside a distribution system, the concentration alone is used. For systems without a treatment plant, however, chlorine may be added in the upstream portion of the system to disinfect water. Therefore, disinfection is increased at higher chlorine concentration levels but also with enough contact time to completely disinfect the water. Therefore the use of the C^*t product as a metric in the distribution system, if no upstream treatment exists, is explored here through computer modeling. The network solver EPANET was used to simulate the C^*t product using water age in a method introduced here. It was found in a demonstration project that increasing the mainline pipe diameter allows the water to slow down enough to allow the C^*t product to fully disinfect the water prior to reaching the first users. Specifically, for the demonstration system analyzed, an 8-inch (203 mm) mainline diameter requires 1.0 mg/L of chlorine addition at the upstream end to fully disinfect the water. This shows promise for the use of pipe enlargement as a disinfection method for systems with no water treatment plant.

Key words | developing country, drinking water, sustainability, water quality, water supply

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INTRODUCTION

Water distribution systems are a complex system of pipes, pumps, and tanks that deliver water from a source to several users (Mays 2000). Every effort is made to ensure that the delivered water is safe to drink (AWWA 2011). This is accomplished in many systems by having a water treatment plant upstream of the distribution system such that water entering the system is potable (Qasim *et al.* 2000). Inside the pipes, however, rust can provide a place for bacteria and biofilms to form that could re-contaminate the water, thereby making it non-potable and possibly harmful to public health (Mays 2000). To disinfect water while traveling through the pipes to the users, a residual level of chlorine is provided as the water leaves the treatment plant and enters the system (AWWA 2011). To ensure adequate treatment, the

concentration-time product (C^*t) is used as a metric for disinfection (Viessman & Hammer 1998). For example, to remove *Giardia muris* cysts a C^*t product of 30–630 mg/L·min is required (Hoff 1986). Inside the system, however, the concentration alone is used for regulatory purposes to ensure adequate disinfection (Qasim *et al.* 2000).

Systems in rural areas and developing countries do not always have treatment plants, however (United Nations 2018). For these systems, water quality can be poor, especially if the water source is from surface water. Lack of sanitation can lead to polluted runoff entering the surface water source. This may necessitate the addition of a disinfectant such as chlorine into the system at the upstream portion or at a storage tank.

Water treatment in the developing world

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

Chlorine as a disinfectant

Solid form chlorine (granular or tablet) is popular in the developing world due to its availability, effectiveness, cost, and relative ease of transportation and use. Chlorine interacts with water to produce hypochlorous acid, *HOCl* (Equation (1)).

This is followed by a disassociation (Equation (2)) of H^+ and hypochlorite ion OCl^- . *HOCl* and OCl^- are known as 'free chlorine.' The concentration of free chlorine remaining in the water after initial disinfection is the chlorine residual (Ratnayaka *et al.* 2017). Chlorine residual continues to provide disinfection in the water system, reducing the risks of recontamination between treatment and consumption:



In chlorine disinfection, pH plays a major role in dictating the dominance of hypochlorous acid and hypochlorite ion. In addition, chlorine concentration values decay with time as the chlorine is consumed in the disinfection process (AWWA 2011).

Drip chlorinators consist of a tank holding a chlorine solution, most frequently created by mixing granular chlorine with water, which drips down into a water reservoir before the contained water flows into the water system (Lewis 2017). Depending on the residence time, a drip

chlorinator may improve disinfection by allowing the chlorine more time to react with the water. In-line chlorinators add chlorine to water as it moves through the pipe. One method of accomplishing this is to add a chamber containing a chlorine tablet to the pipe (Cash-Fitzpatrick 2008; Schuhmann & Karlheim 2012; Yoakum 2013; Wang *et al.* 2015). Diffusion chlorinators function similarly to the in-line tablet chlorinators in that they consist of solid chlorine disbursed into water through erosion. Chlorine tablets are placed in a porous container which is then suspended below the water level in a reservoir. As with drip chlorination this can provide longer disinfection times.

Objective

The objective of this study is to (1) investigate the use of the C^*t product as a metric in the distribution system if no upstream treatment exists and (2) explore the enlargement of the mainline pipe to increase the C^*t product to meet standards, even at a low chlorine dosage. The concept is demonstrated by computer modeling on a real water distribution system.

DEMONSTRATION SYSTEM

The water system of Suyo, Peru (Figure 1) is used for demonstration purposes. The demonstration system consists of a high-elevation reservoir, a 3.9-ft (1.2 m) diameter and 5-ft (1.5 m) depth storage tank, 65 nodes and 86 PVC pipes ranging from 1 to 4 inches (25–101 mm) in diameter (Figure 2). The mainline consists of 4,660 ft (1,420 m) of 4" (101 mm) pipe. There are no pumps and water flows by gravity. The elevation difference between the highest and lowest points is 89 ft (27 m). User demands followed a pattern of higher use in the mornings and evenings and no water usage during the night to reflect the users' practices in this demonstration town (Neff 2018).

Water quality in Peru

During past times of sickness in 1991, a study of some of the municipal wells and private water taps in the city of Piura, Peru found that a majority of those sampled had no chlorine



Figure 1 | Demonstration site of Suyo, Peru. Source: Google Maps.

residual (Ries *et al.* 1992). The city of Trujillo had no chlorination at all (Swerdlow *et al.* 1992). The water treatment situation in Peru has greatly improved since 1991 although much improvement is still needed. In 2015, 95% of the Peruvian urban population and 72% of the rural population were using an improved drinking water source (WHO 2016).

Peruvian water quality limits are stipulated by MINSA (Ministerio de Salud, Ministry of Health) in the Reglamento de la Calidad De Agua Para Consumo Humano (MINSA 2011). Chlorine regulation consists of two parts: 90% of all measurements of chlorine residual taken throughout the water system must be 0.5 mg/L or above, and the remaining 10% cannot be lower than 0.3 mg/L. The minimum water quality regulations mandated by MINSA, the World Health Organization (WHO), and the US Environmental Protection Agency (EPA) are shown in Table 1. Like the WHO, Peru places the maximum safe limit on chlorine residual in drinking water at 5 mg/L. The EPA uses a 4 mg/L maximum (EPA 2018a). To be conservative, 3 mg/L has been used in this investigation.

PROCEDURE

A water network model was formed in the network solver EPANET, which calculates the pressure, flowrate, water age, and chlorine concentration at every node in the system if the information on sources, pipes, and nodes is given (EPA 2018b). EPANET cannot model pH, temperature, or turbidity and, therefore, detailed values of these cannot be reported. A map of the Suyo water system was provided by the Suyo Municipality and transcribed into EPANET. The distance between the reservoir and the town was approximated from GPS coordinates of the reservoir and a known point in the town.

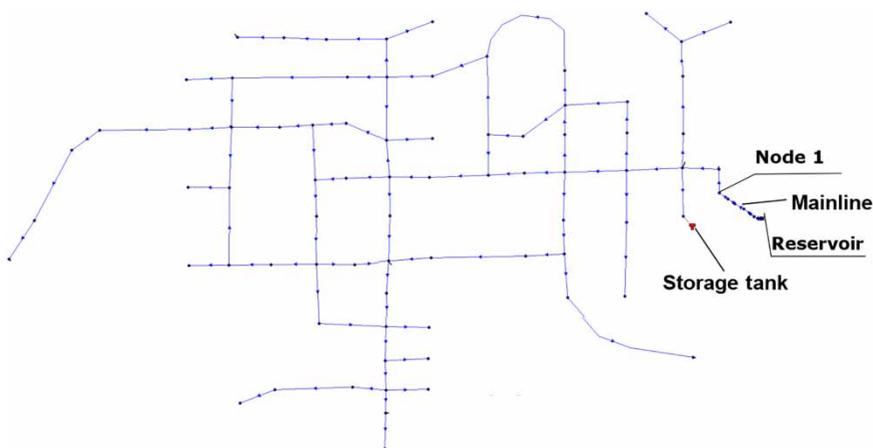


Figure 2 | Suyo water system.

Table 1 | Peruvian water quality regulations

	Peru MINSA	WHO	EPA
Chlorine residual min (mg/L)	90% ≥ 0.5 10% ≥ 0.3	≥ 0.2 (≥ 0.5 in high risk circumstances)	≥ 0.2
Chlorine residual max (mg/L)	5	5	4 (as Cl ₂)
Thermotolerant coliforms (mg/L)	0		
Total coliforms (mg/L)	0		0 (in 95% of monthly samples)
Turbidity (NTU)	≤ 5		≤ 5
pH	6.5–8.5		6.5–8.5 ^a
Conductivity ($\mu\text{mho/cm}$)	$\leq 1,500$		
Total dissolved solids (mg/L)	$\leq 1,000$		$\leq 500^a$

^aSecondary standard.

Source: MINSA (2011), WHO (2017), EPA (2018a).

Individual dwellings were not given their own nodes on the model. Instead, a node was placed at the mid-point of each neighborhood block. Demand for each node was calculated based on the number of homes and businesses fed from that pipeline on the block. This simplification was made to increase clarity of the model. More specific data from the EPANET model appear in Neff (2018).

Population and water usage information was collected next (Table 2). A survey conducted in the neighboring annex of El Jardín in August 2016 found there to be approximately 4.48 people living in each house. Therefore, base demand was calculated with the assumption that five people lived in each occupied house. The map of the Suyo water system showed 281 occupied houses. The population was therefore estimated to be 1,405 inhabitants. This figure is believed to be a reasonable estimation of population growth since the 2007 census (Suyo 2012) at which time the Suyo population was 985.

Table 2 | Population and water usage information

Item	Value	Source
# People per house	5	Census data
# Houses	281	Census data
Population (assuming 5 people per house)	1,405	
Average water usage per person	90 L/day	Ratnayaka <i>et al.</i> (2017)
Factor of safety	1.56	Ratnayaka <i>et al.</i> (2017)

Average water consumption per person was assumed to be 90 litres per capita per day (lpcd) with a factor of safety of 1.56. These numbers were those used by local engineers building and designing equivalent water systems for populations in the hotter regions of Peru where the majority of the population had flush toilets, as was the case in Suyo (Ratnayaka *et al.* 2017). Daily demand patterns were employed in the model based on personal experience by the author. A pattern for residential, office, and school diurnal usage was employed (Neff 2018).

Chlorine decay was modeled as a first-order reaction with a global bulk coefficient of -1.0 (Rossman 2000). Calculating C^*t proved to be a challenge as EPANET reports water age from the reservoir to each node on the system but not from one node to another. One cannot, therefore, directly calculate the influence on the C^*t value from chlorine added at a node part way through the system.

Since this is the first study of its kind and the network solver EPANET used here does not directly calculate the C^*t product, a new method is introduced here to calculate the C^*t values for all runs in which all chlorine was added at the reservoir as follows:

$$C^*t_{ab} = C_b^*(WA_{rb} - WA_{ra}) * 60 \text{ min/h} \quad (3)$$

where

C^*t_{ab} = C^*t value at point b due to chlorine added at point a (min-mg/L),

C_b = chlorine residual concentration measured at point b (mg/L),

WA_{rb} = water age from reservoir to point b (h),

WA_{ra} = water age from reservoir to point a (h),

a = upstream point of analysis, and

b = downstream point of analysis

First, model simulations were run to determine if C^*t values were sufficient to meet Peruvian standards at various chlorine concentration levels. Subsequently, additional model simulations were conducted to determine if enlarging the pipe diameter could bring C^*t values up to standards for cases in which it was found deficient. Contact time is longer in larger pipes since velocity is lower. This is due to the fact that $V = Q/A$ where V is velocity, Q is discharge, and A is the pipe cross-sectional area. Simulations were run for increased sizes of mainline pipe from the original 4" diameters to 5", 6", 7", and 8" (127 mm, 152 mm, 178 mm, and 203 mm, respectively).

The minimum required C^*t value was that required for 3-log inactivation of *Giardia* based on the minimum residual concentration found at Node 1 (Figure 2) after stabilization, based on Peruvian standards. Because the water in Suyo was pH 8.11 when measured it was assumed to have a pH of 8 for the purposes of determining minimum required C^*t . The water temperature was assumed to be 10 °C to be conservative since the average temperature in Suyo is 15 °C and chlorine disinfects less at lower temperatures. C^*t tables can be found in Neff (2018). C^*t values for a 3-log removal of *Giardia* and a 4-log removal of viruses were available and, therefore, were used in this study to test sufficient removal of both. Since pipe diameter was the item being changed in this study, realistic values of the other variables such as pH and temperature were used and held constant.

In addition, enlarging the pipe diameter will increase pressure in the system. All pressure values were checked to ensure that the pressure never exceeded the bursting pressure of the pipe used.

Unfortunately, a lack of measuring equipment and testing laboratories prohibited the taking of actual measurements for model validation.

RESULTS

After modeling a variety of chlorination concentration values it was determined that an adequate C^*t value to achieve 3-log inactivation of *Giardia* was not being achieved. A series of model runs was then conducted with different reservoir chlorine values and diameters for pipes between the reservoir and Node 1 (Figure 2). Node 1 was chosen because it is upstream of the first branching node in the system and, therefore, would ensure all users have potable water. It can be seen (Table 3) that not all chlorine addition values resulted in adequate disinfection by Peruvian standards.

The summarized results show (Table 4) that for a 5" mainline, a 3 mg/L chlorine concentration disinfects before the first users at Node 1. For a 6" mainline only 2 mg/L of chlorine is needed to ensure a high enough C^*t value. For a 7" mainline the needed chlorine value drops to 1.5 mg/L. An 8" mainline, however, yields a sufficiently high C^*t value even for a chlorine concentration of 1 mg/L,

Table 3 | C^*t values (min-mg/L) compared with regulation values for various sizes of mainline (shading means disinfection not acceptable)

Chlorine added (mg/L)	5"		6"		7"		8"	
	C^*t	C^*t min						
1	73	158	98	162	126	162	161	158
1.5	110	168	146	170	188	170	241	170
2	146	174	195	179	251	179	321	179
2.5	183	179	244	190	315	190	401	186
3	220	186	293	197	377	197	482	194

Note: 1 inch = 25.4 mm.

Table 4 | Summarized results of chlorine levels needed for various mainline diameters to achieve disinfection for the entire system

Mainline diameter (inch)	Minimum chlorine level (mg/L)
5	3.0
6	2.0
7	1.5
8	1.0

Note: 1 inch = 25.4 mm.

thereby demonstrating that enlarging the mainline diameter results in sufficiently high C^*t values. For chlorination concentrations greater than 1.0 mg/L all studied pipe diameters delivered high enough chlorine residual throughout the water system to be consistent with Peruvian standards for 3-log *Giardia* inactivation at all studied nodes. Additional details can be found in Neff (2018).

CONCLUSIONS

For the wider water supply sector, the use of C^*t product in the distribution system with no upstream treatment plant gives reliable information that can lead water managers to act, for example by increasing the mainline pipe diameter until the minimum required C^*t value can be achieved, permitting the addition of lower chlorine concentration values.

This work was done remotely, does not have specific implications for the water system used, and has broad applications for the water supply sector.

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