Monitoring of Improvements to Rural Water System Disinfection in Ecuador

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Abstract
Rural Ecuadorian communities rarely disinfect their water supply despite World Health Organization (WHO) and government requirements. Communities which do chlorinate often use methods which do not adequately control the chlorine dose resulting in chlorine taste issues, or a water supply that is not adequately disinfected. In response, *Life Giving Water International* together with *Calvin College Clean Water Institute*, installs and monitors precision chlorine dosing systems in Chimborazo Province to determine whether issues of chlorine concentration variability and low public acceptance can be successfully resolved. A mathematical computer model was constructed for several water systems to predict chlorine levels and the model checked against field measurements. This paper summarizes learning in the areas of chlorine degradation modeling for rural water systems, training on disinfection practices, taste response, management of the chlorine feed solution, and chlorination equipment for rural communities.

Introduction and Background
The World Health Organization's (WHO) standard for the minimum free chlorine residual level in water distribution systems is 0.2 ppm (WHO 2017).[1] In accordance with this standard, the Ecuadorian government requires that communities chlorinate to maintain a minimum free chlorine residual of 0.3 ppm. Maintaining a stable level of free chlorine is challenging in rural sectors of the country. Ecuadorian government promotes simple, economic methods for chlorine disinfection of water systems, which are difficult to control due to the imprecise nature of dosing methods used and variations in water use and demand. Despite being economic, these methods are not received well by the public. The high levels of chlorine produced by these methods often cause people in the rural sector to turn to other, unprotected, sources of water for ingestion.

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[1] WHO notes, "For effective disinfection, there should be a residual concentration of free chlorine of ≥ 0.5 mg/l after at least 30 min contact time at pH < 8.0. A chlorine residual should be maintained throughout the distribution system. At the point of delivery, the minimum residual concentration of free chlorine should be 0.2 mg/l."

In response to the need, *Kawsaypak Yaku*[2] and *Life Giving Water International*[3] equipped ten community water systems with precision dosing pumps for chlorination disinfection to determine if this more advanced approach would help communities solve chlorine taste issues, maintain acceptable chlorine levels, and improve public acceptance of chlorinated water. In addition, technical support, follow-up, and additional resources are provided to help communities successfully chlorinate. *Calvin College Clean Water Institute*[4] provides technical support, periodic monitoring of chlorine levels, and some oversight for this project.

Since the distances and elevation differences can make water hauling arduous, currently built water systems in rural Ecuador normally provide a metered spigot for each home, as shown in Figure 1. Water metering enables the community to better manage their water supply by controlling water use, covering costs, and keeping system pressure.

Figure 1 Typical concrete pedestal mounted metered spigot for a Kichwa home

Most Ecuadorian rural communities build, manage, and operate their community water system with limited help from government. They dig pipe trenches, as shown in Figure 2, and build reservoir structures by *mingas*, which are community work bees. Since health care resources can be difficult to access for remote rural communities, it is crucial that their water system provide reliable water quality and constant service to each home so that water transmitted disease is minimized. Water disinfection is only one of the many issues that are worthy of investigation to improve rural water supply in the Andean countries. A study by CARE and the Ecuadorian government in 2005, indicates that only 13% of rural Ecuadorian water systems are considered to be sustaining (Solis, 2006).

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[2] *Kasaypaku Yaku* is a *Kichw*a Ecuadorian Christian ministry providing technical assistance to rural communities designing, building, and/or improving their water system. *Kawsaypak Yak*u means "water that gives life" in the *Kichwa* language.

[3] *Life Giving Water International* is a US based Christian charity which provides resources, funding, and internship opportunities to facilitate clean water ministry in developing countries. www.lgwi.org

[4] https://calvin.edu/centers-institutes/clean-water-institute/about/

Figure 2 Kichwa communities normally build their own water system themselves.

Monitoring Study

To increase the success of rural chlorination within communities, *Life Giving Water International* has partnered with the *Calvin College Clean Water Institute* to monitor free and total chlorine residual levels in a number of communities. Intensive monitoring was done in Achullay, Ocpote la Merced, and Castug Tungurahuilla, three indigenous communities within Chimborazo Province (see Figure 3). The purpose of the monitoring was to check chlorine residual concentrations within several community water systems with precision dosing pumps and to characterize the chlorine decay coefficients that should be used to model chlorine residuals in computer models such as the U.S. Environmental Protection Agency program EPANET. The bulk decay coefficients were also determined separately by conducting chlorine degradation tests based on the *protocol for chlorine decay bottle test* described in the AWWA Manual 32 (AWWA 2017).

Figure 3. Community Locations

Chlorine Monitoring in Achullay, Ocpote la Merced, and Castug Tungurahuilla

To verify decay parameters for hydraulic models of chlorine residual, field measurements were made with the help of interns and student teams from Calvin College. Measurements were made on three trips to Ecuador - May 2017, January 2018, and July 2018. In each of the communities, between 10 and 35 representative taps were selected. Samples were taken at the dosing source, at the storage reservoirs, and throughout the primary branches of the distribution network. Since many homes are vacant due to families moving to the cities, only taps of houses with frequent water use were measured.

Chlorine residual was measured at each tap using program *80 Chlorine F&T PP* on a HACH DR 900 Spectrometer following the USEPA DPD Method. Before preparing the water samples, the tap was run to flush out stagnant water. Two 10-mL samples were prepared for both free and total chlorine. Each sample was read three times using the spectrometer. The average of these six values was used as the residual at the tap.

Chlorine Degradation Test Description

Four liters of unchlorinated water was taken from the supply point for each community. It was then dosed with locally sold bleach, advertised to have a 5.25% concentration. Ten sealed, glass containers were filled such that no headspace was present with the dosed water. The glass containers were submerged in a water bath and protected from sunlight to maintain a consistent temperature throughout the duration of the experiment and simulate the conditions present in the distribution system. The concentration of both free and total chlorine were measured immediately, after six hours, after 24 hours, and after increments of 24 hours thereafter. The measured chlorine residuals were graphed as a function of time using Microsoft Excel. An exponential trendline equation was fit to the data. The bulk decay coefficient was determined from the trendline equation.

Results

One of the goals of this study is to provide tools for improved water system design. Computer software, like EPANET, can be used to help design a new water distribution system as well as model the fate of chlorine throughout proposed and existing systems. To effectively use such a model the parameters associated with chlorine decay need to be characterized. EPANET allows the user to specify decay coefficients associated with reactions in the bulk fluid as well as reactions at the pipe wall (Rossman 2000). The "bulk" and "wall" decay coefficients will be characterized using data from chlorine degradation tests as well as sampling throughout the distribution system.

Chlorine Degradation Test Results

Chlorine degradation tests were performed with water taken from both Achullay and Castug Tungurahuilla. The tests assumed a first order reaction,

$$\frac{dC}{dt} = k_B C$$

where C is the free chlorine residual and $k_B$is the bulk decay coefficient (dimensions of inverse time and negative value). Solving for C yields

$$C = C_0 e^{k_B t}.$$

The data from both communities were normalized using the initial concentration measured just after mixing. The results show a very similar pattern (see Figure 4). The normalized data from both locations were combined and an exponential trend line computed. The bulk decay coefficient was computed to be -0.052 [1/day]. The regression R^2 is 0.78.

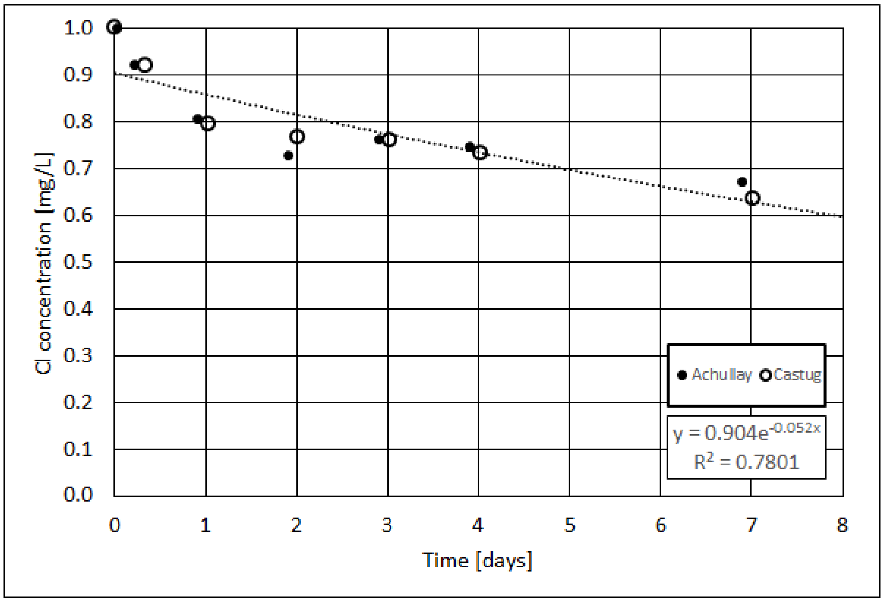

Figure 4. Regression Results for Bulk Decay Coefficient

Hydraulic Modeling of Chlorine Residual

Hydraulic modeling was performed to characterize the chlorine decay associated with reactions within the distribution system. Here chlorine degradation occurs with both the bulk fluid and the pipe walls. The equation describing first order decay including both bulk and wall reactions is

$$\frac{dC}{dt} = k_B C + \frac{A}{V} k_W C$$

where k_W is the wall decay coefficient (dimensions of length over time) and $\frac{A}{V}$ is the surface area per unit volume inside the pipe. For a circular cross section this is 4 over pipe diameter, or

$$\frac{dC}{dt} = (k_B + \frac{4}{D} k_W) C$$

Solving for concentration

$$C = C_0 e^{(k_B + \frac{4}{D} k_W) t}$$

The original goal of this phase of the study was to measure chlorine concentrations at multiple locations throughout several communities on several occasions. Once these measurements were made, the decay parameters could be determined via hydraulic modeling.

The first challenge was monitoring systems with adequate levels of chlorine to record reliable data. Achullay and Castug Tungurahuilla were visited 3 times and Ocpote La Merced twice. In many cases, the communities were under dosing leading up to the time of measurement at the source resulting in free chlorine concentrations that were too low relative to the precision of the measuring equipment. In one case, the community of Castug Tungurahuilla was not pumping any chlorine solution because the suction tubing rose to the surface so that the dosing pump pumped air. The problem was not noticed for about two weeks, so we were not able to make valid chlorine measurements in the community in July 2018, as we had hoped, since it would have taken another month to stabilize chlorine levels again.

The analysis performed was for the two cases with the highest average free chlorine concentrations. These two cases were for Achullay and Ocpote la Merced both in July 2018. Figure 5 shows the results of sampling done in Achullay. This figure shows the storage reservoir in the upper right corner as well as a pressure break tank along the line heading to the lower left corner. It also shows the pipes along with the diameters. The circles classify the free chlorine concentrations into three groups. The black circles represent the higher values and tend toward the tank while the gray and white circles tend to the outer branches of the network. As can be expected there are always outliers.

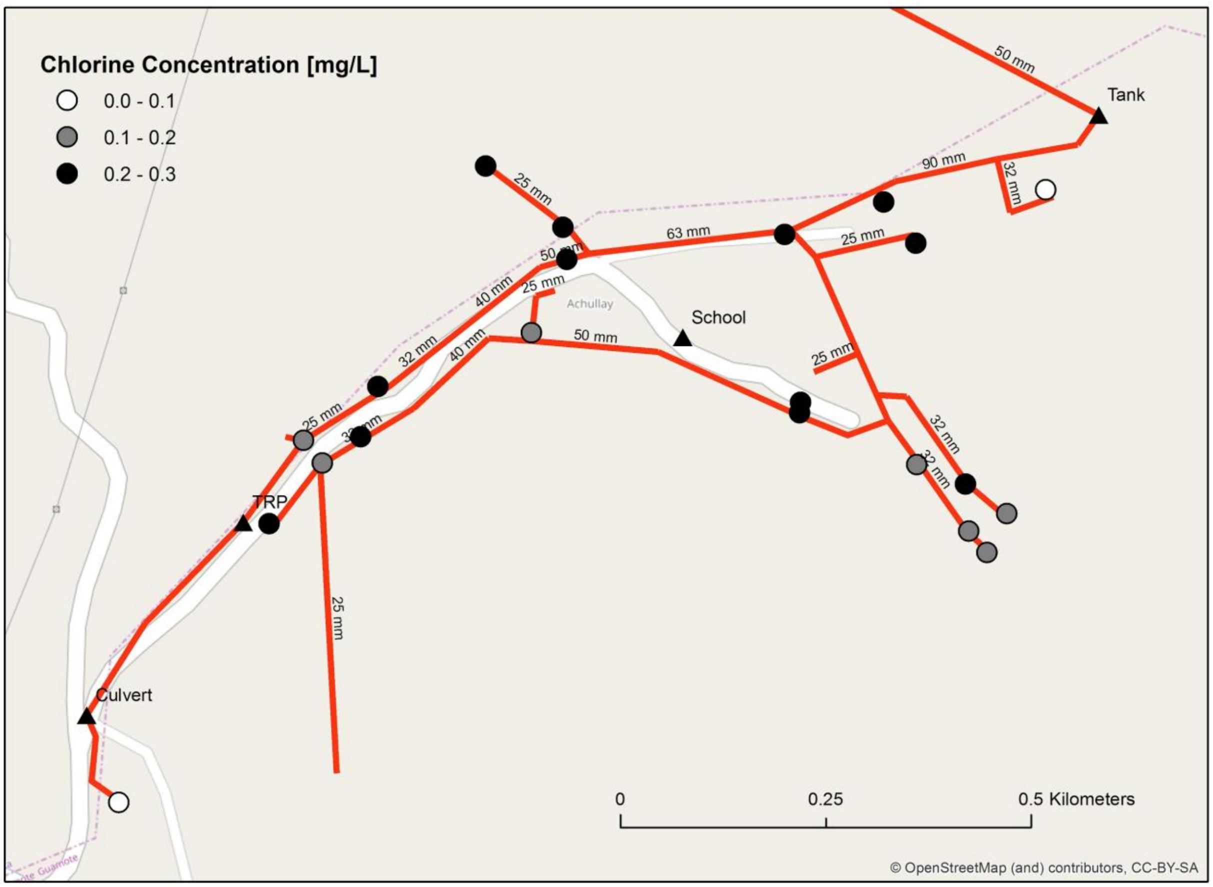

Figure 5. Free Chlorine Residual, Achullay, July 2018.

The second challenge was to use this data to extract information about the chlorine decay coefficients. One option was to simply model the system using EPANET and vary the coefficients until a reasonable match was found. This would have been time consuming and would not provide any way for optimization.

The approach taken instead was to develop a spreadsheet based model of the system from the reservoir to each model junction. Using junction demands based on average per household water use rates, a spreadsheet can be developed to compute the discharge in each pipe in the network. (This is easy because there are no loops in the network). The equation for the chlorine concentration can be re-written to account for flow through the pipes between the tank and each monitoring location.

$$C = C_0 e^{\left(k_B \sum t_i + 4 k_W \sum\left(\frac{t_i}{D_i}\right)\right)}$$

Here t_i and D_i are the travel time and diameter for each pipe along the flow path from the reservoir to a monitoring location. The results using specific values of the two decay coefficients matched the results obtained with an EPANET model. With the spreadsheet it was possible to compute the error between the modelled concentration and measured values. Excel's Solver function was used to vary the decay coefficient(s) to minimize sum of squared residuals (SSR).

Table 1 shows the results for Achullay and Ocpote la Merced. The Ocpote la Merced system is fed from two different reservoirs so a separate analysis was done for each. For each location two cases were performed. In the first case the wall coefficient was set to zero and the optimization was used to determine only the bulk coefficient. In both cases a value was found that had a higher absolute value than the -0.052 [1/d] found by the chlorine degradation test, indicating that wall decay is likely significant. In the second case the bulk decay coefficient was set to -0.052 [1/d] and optimization was used to determine the wall decay coefficient. The wall decay coefficient varied between -0.001 and -0.011 [m/d].

Table 1. Optimized Decay Coefficients

Community	Number of data values	Average Free Chlorine Concentration [ppm]	Case	Bulk Decay Coefficient, k_B [1/d]	Wall Decay Coefficient, k_W [m/d]	Coefficient of Determination R^2
Achullay	21	0.21	k_B optimized	-0.586	--	0.225
			Set k_B and optimize k_W	-0.052	-0.0063	0.366
Ocpote la Merced - east	12	0.52	k_B optimized	-0.184	--	0.130
			Set k_B and optimize k_W	-0.052	-0.0010	0.147
Ocpote la Merced - west	8	0.37	k_B optimized	-1.731	--	0.823
			Set k_B and optimize k_W	-0.052	-0.011	0.772

Several conclusions can be drawn from these results. First, the average free chlorine concentrations for these communities were at the low end of the recommended levels. Unfortunately, these three cases were the highest levels monitored. In total, monitoring was done in 3 communities with a total of 8 rounds of sampling. The first round of sampling in Achullay resulted in an average free chlorine concentration of 0.11 ppm. The first round in Ocpote la Merced resulted in an average free chlorine concentration of 0.05 ppm. So, these communities are struggling to reach appropriate disinfection levels.

The estimated decay coefficients varied quite a bit and the coefficient of determination (R^2) values are rather low. The low R^2 is a result of a lot of noise in the data. Some home taps may not have been used for several days but the model assumes a uniform demand. The variation in values of the decay coefficients at least allows the modeler to generate a set of possible scenarios regarding chlorine concentrations. It also points to the need for more sampling.

It should be noted that the water temperature used in the degradation tests was different than that in the water systems. The water temperature in Achullay was measured at 12°C. It can be assumed that this temperature is consistent across communities since the distribution system is underground. However, the degradation tests were conducted between 17°C and 19°C.)

Application in Rural Ecuador

Training

While it is important to be able to model chlorine residual levels accurately, training community members to operate and maintain their system is equally as important. The community of Troje, which has chlorinated their water supply for about a year, lost their *aguatero*, or water system operator, when he died in May 2018. Since he was the only community member that knew how to operate the water system, disinfection ceased to operate upon his death. To prevent this from happening to other communities, adequate training should be made available to everyone in the community involved in the operation and maintenance of the water system.

In response to water system maintenance education needs, *Life Giving Water International* held a chlorination workshop in coordination with the local government in 2017 and 2018. The workshops included both lecture and hands-on workstations. The attendees learned common problem prevention, chlorine residual measurement, and disinfection system maintenance.

Another important element of the workshop was sharing experiences. While *Life Giving Water International* had technical knowledge, each community had different experiential knowledge. The opportunity for *Life Giving Water International* to learn from the communities experiences and for the communities to learn from each other's experiences was valuable.

Public Taste Response

Understanding public taste response can be challenging to quantify as it involves social and psychological sciences. There are certain soft science factors that go beyond the extent of this study that could affect the accuracy of public taste response results relating to the social standing, educational background, and culture of rural communities compared to those collecting the data. It is important to note that community members tend to agree to requests made by *Life Giving Water International*. However, when it comes to public perception of water, it seems that they have two conflicting desires. One is to please *Life Giving Water International* by chlorinating at the proper rate and reporting good results. The other is to appease the community by reducing the dosing rate.

To better understand public response to chlorinated water, community members were asked how the water tasted during the data collection process. Some members of the communities responded positively, while others responded negatively. Some even reported that the water tasted so bad that even their livestock rejected it.

In response to the lack of public acceptance of chlorinated water in rural Ecuador, the *Calvin College Clean Water Institute* conducted a study in partnership with LGWI in 2017 (Stout, et.al. 2018). This study aimed to determine the chlorine residual concentration range that would provide both potable and publicly accepted water. The study was also designed to determine if previous experience with chlorinated water made the subject more or less sensitive to the chlorous flavor. To determine this, participants from rural Ecuador and participants from Grand Rapids, Michigan participated in a taste test. Each participant received six sets of two samples of water, one chlorinated (at increasing concentration levels of 0.0 mg/L, 0.1 mg/L, 0.3 mg/L, 1.0 mg/L, 2.0 mg/L, and 3.0 mg/L) and the other unchlorinated. They were asked to determine whether one was chlorinated and if so, which one. Then they were asked to rate the palatability of the sample using a sliding scale from pleasurable to unpleasurable. Finally, they were asked whether or not the water would be accepted for ingestion if it came out of the tap in their household. The two groups of participants were compared against each other to determine the effects of previous experience drinking chlorinated water. Rural Ecuadorians have only limited familiarity with chlorine disinfection of their water supplies, though liquid laundry bleach (5.25% sodium hypochlorite) is readily available. The majority of US participants' primary source of water was chlorinated.

The study determined that participants with less previous experience with chlorinated water were more sensitive to the chlorous taste. It recommended that chlorine residuals within Ecuadorian water systems were maintained above the 0.3 mg/L required by the government but below 1.0 mg/L to deliver water that is both palatable and potable. It also recommended that when exposing a community to chlorinated water for the first time, to maintain low levels of chlorine and increase them over time so that they can become accustomed to the taste. An additional recommendation was that the chlorine content be measured upon receipt of a water flavor complaint since the study witnessed rejection at all chlorine levels whether or not the participants could accurately distinguish the chlorous flavor.

A complicating factor which was not adequately anticipated was the oxidation of the biological film developed in these water systems prior to initiating the chlorine disinfection. One reference (Letterman 1999) points out that when chlorine disinfection is initiated in a water system not previously disinfected, an initial increase in consumer complaints regarding taste & odor can be expected due to chlorine oxidizing organic matter (e.g. biological film on the pipe interior and wetted surfaces of storage structures in the distribution system). In Ocpote la Merced, one of the study communities, it appeared that the chlorine taste diminished when the water system disinfection stabilized and the organic material was oxidized.

At the chlorine disinfection workshop additional, informal taste testing was conducted. Most participants sampling the disinfected Ocpote la Merced water found the water quite palatable and many said the taste was as good as or better than the unchlorinated, bottled water sample. Further study is necessary to determine the best method to oxidize the organic material without creating strong public complaint and to determine how long the taste and odor issues continue in a newly chlorinated water system.

Current Chlorination Practices

The government primarily promotes using solid calcium hypochlorite tablets for rural chlorination systems. Generally, a controlled shunt flow of water passes the chlorine tablet slowly dissolving the calcium hypochlorite and distributing chlorine throughout the water system. While this approach is both simple and economic, it is difficult to control the chlorine concentration in the water. As demonstrated through the taste study, people in rural Ecuador are sensitive to chlorous flavor. This often leads to a lack of public acceptance of chlorinated water.

Life Giving Water International has worked with ten communities in rural Ecuador to implement precision dosing solutions. In most of those communities the chlorine feed solution of approximately 1% was prepared initially using granular calcium hypochlorite, also known as HTH. Dosing pumps were initially adjusted to dose the water supply flow at approximately 1 ppm to maintain a 0.3 ppm residual in the extreme parts of the system. Many of the communities requested that the dose be reduced to 0.8 ppm.

The dosing pumps are controlled from the electric pump panel as shown in Figure 6, so that they only operate when the main water supply pump is on. In all cases, the water supply pumps are submersible well pumps. The chlorine feed is directed to the pump suction so that the chlorine is mixed in the pump and has significant contact time in the pressure pipe feeding the main storage reservoir and the reservoir itself.

Figure 6 Water system operator for Achullay and electrical panel controlling the water supply and chlorine dosing pumps. Note the two peristaltic dosing pumps, one for each water supply pump, and the blue chlorine solution feed tank.

All of the water systems studied use protected groundwater as the water source either from a dug well or a spring protected using a subterranean collection system completely sealed by concrete so that only filtered groundwater enters the water system. The high quality groundwater has minimal organic content and hence a minimal chlorine demand.

Granular calcium hypochlorite initially used to produce the 1% feed solution, proved to be unsatisfactory due to difficulties in dissolving and re-crystalling in the dosing pump discharge. Due to these problems, liquid sodium hypochlorite was used in the form of laundry bleach (5.25% sodium hypochlorite) and diluted to a 1% solution. Since chlorine bleach is easily available, the communities can be independent of government or other agencies for their chlorine supply.

Generally, the communities use a feed tank of 60 to 80 liter capacity. Since their water use ranges from 100 to 500 cubic meters per month, the feed rate of the chlorine feed solution is about 10 to 50 liters per month. Additional study is needed to determine the stability of the chlorine feed solution to make recommendations to communities regarding any adjustments required to maintain a constant chlorine dose.

The *aguatero*, water system operator, is responsible for measuring the chlorine residual level at least one spigot each week. This is a good indicator of whether or not the dosing pump and chlorine feed solution are working correctly. Each month they measure the chlorine residual at an extreme in the system. This helps them determine if the dosing pump rate needs to be increased, decreased, or maintained. The frequency of measurements is kept low to be sensitive to rural Ecuadorian culture.

Each community has a Hach Free Chlorine Color Disk Test Kit. This kit consists of a color comparison disk and two plastic vials. To measure chlorine residual using this kit, 5 mL of water is added to each vial. One is used as a blank while a DPD Free Chlorine Powder Pillow for 5-mL samples is added to the other. After mixing for at least 20 seconds, the colors are compared in front of a light source. The color disk increases by two tenths with each color step. Using this measurement method, it is reasonable to believe that chlorine concentration is accurately measured to the nearest tenth.

Conclusions

When working in rural communities with little experience with chlorinated water, it can be challenging to implement chlorine disinfection. While there are simple and economic methods of chlorine disinfection, they often lead to rejection by the community due to the pungent chlorous flavor caused by inconsistent chlorine levels. When this happens, the disinfection no longer serves its purpose of improving public health.

The chlorine residual monitoring study provided some insight regarding values of the chlorine decay coefficients. This will provide valuable information for future computer modeling of free chlorine concentrations in water systems in this region. Further monitoring should still be done. The monitoring study also made clear the difficulty of reaching the prescribed targets for free chlorine in these water systems.

Even with precision pumping, taste issues occur in some communities with free chlorine residual levels well below 1 ppm. It is probable that the pungent flavor of the water is due to the oxidation of organic matter on the system's wetted surfaces. Further study needs to be conducted to determine the origin of the taste complaints related to flavors caused by chlorination. When chlorine can be tasted in a system, the users often pressure the water system operator to reduce the chlorine dose. This may reduce the free chlorine residual below the WHO standard of 0.2 ppm, and therefore not adequately serve the purpose of disinfection.

When implementing a disinfected water system into a rural community, it is recommended that the target chlorine residual levels are maintained between 0.3 and 1.0 ppm to have adequate disinfection while remaining below the level at which people can distinguish the chlorous flavor. Training on how to maintain and operate the system should be made available to multiple members of the community to enable them to be independent of outside agents. Finally, at a minimum, chlorine levels should be measured to check functionality of the system at least once a week and to check chlorine residual in the extremes of the system at least once a month.

Acknowledgements

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