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EVALUATION OF SUITABLE AUTOMATIC CHLORINATION DEVICES FOR GRAVITY-DRIVEN MEMBRANE WATER KIOSKS IN UGANDA

Master Thesis

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Abstract

Between 2014 and 2018, gravity-driven membrane (GDM) water kiosks were established in Eastern Uganda. Although water is safe at the point of delivery, it gets contaminated during storage and transport. Chlorination can provide effective protection against recontamination. Therefore, the goal of this master thesis is to investigate, if the automatic chlorination devices Venturi and Chlorine Dosing Bucket (CDB) can sustainably be applied in combination with GDM systems to provide a stable level of free residual chlorine (FRC) in the treated water at the tap. Measurements of FRC concentrations and the flow rates at the taps were conducted to assess the installation of the devices as well as the provision of stable FRC levels in the treated water provided at the tap. Chlorine decay during transport and storage was determined in 57 jerry cans by measuring FRC concentrations 0 h, 0.5 h and 24 h after filling the jerry cans. After 24 h also the water quality of the drinking water was determined in these jerry cans. Moreover, the taste acceptability of chlorine by the local community was evaluated with the help of surveys and chlorine tastings. Both automatic chlorination devices could be successfully installed at the GDM water kiosks. A stable level of FRC in the treated water at the taps, however, could not be provided by both of them. A sustainable implementation is only possible in the case of the CDB. The CDB is affordable, can be produced locally, and operation by the local community is possible. In contrast, the Venturi has to be imported from overseas and the costs cannot be supported by the local people. Furthermore, it was found that on average 1.8 mg/L of FRC decays in the course of 24 h. Only if the chlorine concentration was above 0.4 mg/L after 24 h, no *E. coli* were detected in the water after 24 h of storage. No clear answer can be deduced from the chlorine tastings due to confounding effects such as perceived social obligations and non-randomization of the sample distribution. The findings of this study indicate that an FRC level of 2 mg/L at the tap of the water kiosk is not sufficient to guarantee satisfying quality of drinking water after 24 h of storage in jerry cans. Neither the Venturi nor the CDB does achieve adequate chlorination at the GDM water kiosks. Nevertheless, the CDB has some characteristics that are crucial for the study area such as the provision of a local supply chain and its affordability. Therefore, mitigation strategies were developed for the CDB. The strategies include the application of two different slit openings, the reduction of the water flow to the chlorine bucket and the increase of the chlorine bucket volume. Future research should investigate if the CDB provides more stable FRC levels in the treated water provided at the tap by implementing these strategies.

Contents

Glossary

CDB	Chlorine dosing bucket.
DPD	Diethyl-p-phenylenediamine.
FRC	Free residual chlorine.
GDM	Gravity-driven membrane.
UGX	Ugandan Shilling.
WHO	World Health Organization.

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1 Introduction

This master thesis begins with a short background orientation on the importance and the provision of safe drinking water. In Chapter 1.2, first, the technical set-up of gravity-driven (GDM) water kiosks is explained. Second, the motivation for employing chlorination at these water kiosks is presented. Subsequently, the process of chlorine disinfection is outlined in Chapter 1.3. Finally, Chapter 1.4 provides an overview of the available automatic chlorination devices suitable for low-income countries.

1.1 Background

The World Health Organization (WHO) (2018) estimates that at least 2 billion people rely on a source of drinking water contaminated with faeces. Moreover, access to an improved source of drinking water is absent for over 844 million people, including 159 million people depending on surface water such as lake water. Contaminated water is a potential transmitter of diseases such as typhoid, cholera, dysentery, polio, and diarrhoea, which account for roughly 502'000 diarrhoeal deaths every year (WHO, 2018). The global importance of safe water for development, poverty reduction, and health is reflected in the United Nations Sustainable Development Goals (SDGs), which form the basis for the 2030 Agenda for Sustainable Development adopted by all United Nations (UN) Member States in 2015 (UN, n.d.). It is a declared target of SDG 6 to guarantee "universal and equitable access to safe and affordable drinking water for all" by 2030 (UN, 2017).

Conventional approaches like the construction of deep tube-wells and extensions of piped water services have often failed to improve access to safe water, especially for the most vulnerable populations in urban slums and rural areas (Kirkpatrick, Parker, & Zhang, 2006). Therefore, alternative technologies at the point-of-use, also called household water treatment technologies, have been developed to improve access to safe drinking water in low-income areas (Pickering, 2014). Although several studies provide support of the efficacy of such solutions in field trials, household demand for such technologies as well as the sustained use of household water treatment systems remains low (Luby et al., 2004; Stockman et al., 2007; Luby, Mendoza, Keswick, Chiller, & Hoekstra, 2008). For several reasons water kiosks provide a promising solution to ensure a safe water supply under these conditions (Sima, Desai, McCarty, & Elimelech, 2012; Opryszko et al., 2013). First, water kiosks can be erected based on actual demand and are flexible with regards to local conditions. Second, they provide a large population with access to safe drinking water while incurring less investment costs compared to piped water supplies. Third, water kiosks do not demand significant behavioural changes from the target population (Opryszko, Huang, Soderlund, & Schwab, 2009). Safe water kiosks represent decentralised water treatment systems on a community level. They run in parallel to governmental water infrastructure and drinking water can directly be purchased at these kiosks (Sima & Elimelech, 2013).

1.2 GDM Water Kiosks for Drinking Water Treatment

Since July 2010, the Swiss Federal Institute of Aquatic Science and Technology (Eawag) has been working on an innovative water treatment technology that can be utilised for safe water kiosks (Peter-Varbanets, Johnston, Meierhofer, Kage, & Pronk, 2011). The basis of these safe water kiosks is a gravity-driven membrane (GDM) filtration. Disinfection is achieved by ultrafiltration membranes with a pore size of 20–40 nm. The pressure needed for ultrafiltration is acquired by gravity. Ultrafiltration serves as an effective physical barrier for suspended particles, colloids, and all three classes of pathogens: protozoa, bacteria, and viruses (Peter-Varbanets et al., 2011). Conventional filtration systems depend on regular cleaning and flushing to avoid fouling which can lead to flux decline and clogging of the membrane. In contrast, GDM filtration can be operated for five to eight years with no need for maintenance, even if turbid water is treated. This is made possible because of the formation of a porous biofilm on the membrane at low water pressures. The biological activity in the biofilm leads to the formation of cavities. As a result, the biofilm turns porous and allows the passage of water. An equilibrium is established between the deposition of organic matter and bacterial activity, leading to a low but stable flux (Peter-Varbanets et al., 2011). As a result, GDM systems offer the significant advantage of functioning without regular cleaning and disinfection or electricity. For these reasons, GDM water kiosks are a suitable option for drinking water provision in remote areas where water systems are managed by local communities (Peter-Varbanets et al., 2016).

In collaboration with the local partner organisations Water School Uganda and Africa Water Solutions, Eawag introduced three GDM water kiosks next to schools in Eastern Uganda between 2014 and 2016. The share of people who use untreated lake water as drinking water was reduced from 73% of 316 interviewed households before the establishment of the kiosks to 41% by 2016. Further, 58% of the questioned households used drinking water from the kiosks by 2016 (Peter-Varbanets et al., 2016). Per day, the water kiosks treat up to 6'000 L of water that is first pumped from Lake Victoria to the raw water tank using a solar pump. Additionally, during the rainy season, rainwater harvested on the roof of the nearby school is piped to the raw water tank. The raw water flows according to the principles of gravity to the membrane tank, where the membrane filters the water. The pressure, which is required to press the water through the membrane, is also created by gravity, which is achieved by differing water levels between the tanks. Purified water is collected in the clean water tank, which is around 1 m above the outflow to guarantee low but sufficient pressure in a kiosk's four water taps that serve to distribute water to costumers (Peter-Varbanets et al., 2017). Since May 2018 two additional water kiosks – with two significant adjustments – are in operation in the study area of this thesis. The first adjustment is the higher construction of the tanks' foundation to increase the flux at the taps. Due to this adjustment, however, rainwater can no longer be harvested from the schools since the gravity difference is too low. Second, the raw water is piped directly into the membrane tank (H. Ouma, personal communication, October 11, 2019). Customers collect the water in 20 L water storage containers (called jerry cans) whose original use was the storage of vegetable oil (Meierhofer et al., 2017).

Meierhofer et al. (2017) showed that water was safe at the investigated water kiosks but got contaminated when filled into unclean jerry cans. Wright, Gundry, & Conroy (2004) conducted a meta-analysis of 57 studies and concluded that microbiological contamination of water between the source and its point-of-use is widespread and often significant. Unhygienic water-handling practices, unclean containers, and contamination from the ambient environment contribute to deteriorating water quality (Jagals, Bokako, & Grabow, 1999; Nala, 2001; Theron, 2000). Other studies (Momba & Kaleni, 2002; Jagals, Jagals, & Bokako, 2003; Mellor, Smith, Samie, & Dillingham, 2013) observed regrowth of microorganisms on the surface of household containers during transport and storage which negatively affected water quality.

Several disinfection techniques such as ultraviolet light, ozonation, or chlorination exist. Only chlorine, however, provides residual protection against recontamination during transport and storage (WHO, 2012). Diener et al. (2017) showed that chlorination is an affordable, easy to handle, and effective method to deactivate *E. coli* by providing protection through residual chlorine from the reservoir to the household storage level. Dössegger & Meierhofer (2018) found that chlorination can improve water quality at the point of consumption in households in Eastern Uganda. Nevertheless, high levels of turbidity in the water can protect pathogens from the effect of disinfection, thus stimulating the growth of bacteria and causing significant chlorine demand. Yet, in combination with a filtration system such as the GDM water kiosks, chlorination could prove to be a promising option for the treatment of drinking water. Also Meierhofer et al. (2017) pointed out that recontamination of raw water from Lake Victoria filled directly into uncleaned jerry cans could not be prevented by chlorination alone. Only the combination of ultrafiltration and chlorination is able to prevent regrowth and recontamination of drinking water in the jerry cans during transport and a storage period of 24 h (Meierhofer et al., 2017).

1.3 Chlorine Disinfection

Disinfection is the partial destruction and inactivation of pathogenic microorganisms due to either physical processes (UV irradiation) or exposure to chemical agents such as chlorine (Crittenden et al., 2012). Chlorine is a strong oxidant and reacts rapidly with various kinds of inorganic and organic material including cell walls, DNA, and enzymes. The exact mechanisms in the pathogen inactivation, however, are not well known (Johnston, 2018). The amount of chlorine added to water is called chlorine dose (WHO, 2017b). Independent of its form (gas, solid, or liquid), chlorine transforms into hypochlorous acid (HOCl) upon contact with water. HOCl can dissociate to hypochlorite ion (OCl^-). HOCl is the predominant species below a pH value of 7.6, whereas OCl^- is the predominant species above this value. HOCl disinfects faster than OCl^-. Therefore, a pH value below 7.6 is beneficial where disinfection alone is concerned (Crittenden et al., 2012). HOCl and OCl^- react with reducing agents (e.g. iron), organic matter and ammonia present in the water. The chlorine consumed during those reactions is called chlorine demand. Depending on the water quality, the chlorine demand changes (WHO, 2017b). The chlorine remaining after chlorine demand has been satisfied is referred to as total chlorine residual. Total chlorine residual is further subdivided into free residual chlorine (FRC) and combined chlorine (see Figure 1). Combined chlorine is the amount of chlorine that had reacted with ammonia in the water. These compounds, which are also called chloramines, have only weak disinfection capacity. In contrast, FRC is the chlorine available to inactivate disease-causing organisms (WHO, 2017b).

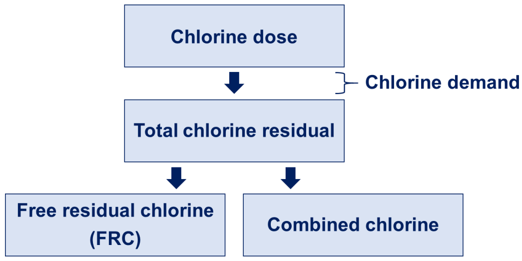


Figure 1: Chlorine addition flow chart (adapted from WHO, 2017b)

The chlorine dose has to be sufficient to meet both the chlorine demand and to generate a residual that is strong enough to eliminate pathogens. However, chlorination efficacy does not only depend on chlorine concentration but also on contact time with pathogens. Chlorine needs sufficient time to destroy or inactivate microorganisms during disinfection. If the water temperature is higher or pH values or water turbidity are lower, contact time or chlorine concentrations can be reduced (WHO, 2017b). The effectiveness of chlorination is measured with the Ct value. This value is calculated by multiplying the FRC concentration (C) at the end of the contact time by the amount of time (t) water is in contact with FRC. WHO (2017a) recommends a minimum Ct value of 15 min.mg/L. This Ct value corresponds to a contact time of at least 30 min with a residual chlorine concentration of ≥ 0.5 mg/L, whereby the pH value of the water is below 8. With these parameters, most of the harmful microorganisms associated with waterborne diseases such as bacteria and the majority of viruses are removed. Chlorine, however, is not very effective against some protozoan pathogens, in particular not against *Cryptosporidium*, which is a significant cause of child diarrhoea (WHO, 2017a).

Chlorination of the drinking water can happen either automatically at the water kiosk (point-of-collection) or manually in the households (point-of-use). By conducting a systematic review and meta-analysis of 21 studies, Colford & Arnold (2007) concluded that point-of-use chlorination technologies reduce both, the risk of stored water contamination with *E.coli* and childhood diarrhoea. Some studies (e.g. Luby et al. (2004); Stockman et al. (2007); Luby et al. (2008)), however, have found that household demand and sustained use of household water treatment technologies remain low despite active promotion. A significant barrier to consumer adoption of point-of-use technologies is the formation of new habits by the consumer, often imposing a substantial burden on time every day (Luby, Mendoza, Keswick, Chiller, & Hoekstra, 2008; Luoto et al., 2011). Automatic technologies at point-of-collection are promising because they are affordable for low-income countries and require minimal behavioural adaptions (Pickering et al., 2015).

1.4 Automatic Chlorination Devices

Skinner (2001a) provides an overview of the chlorination devices that do not require chlorine gas or electricity and are thus suitable for community water supplies in rural areas of developing countries. He divides these devices into three categories: water-powered devices, diffusion chlorinators, and gravity-driven chlorinators. In gravity-driven chlorinators, the dosed chlorine solution is driven through the device exclusively by gravity. An example for such a device is the Mariotte Jar, which makes use of a siphon to maintain a constant pressure that ensures a constant chlorine drip rate out of the system. Gravity-driven chlorinators are not suitable for intermittent flows of water as observed at the investigated water kiosks. In water-powered chlorinators, the moving water powers a mechanical device or generates a reduced pressure, which is used to dose the chlorine solution into the water (Skinner, 2001a). The MSR Venturi is such a device. It creates a pressure differential that is used to suck in the liquid chlorine into the flowing water (MSR Global Health, n.d.). It was decided to investigate this device in this thesis for two reasons: First, the Venturi was successfully tested in a similar context, namely at water kiosks in Kenya. Second, the dosing of the Venturi should stay relatively constant in spite of the flow rate variation (SWAP, 2017). This is crucial for the investigated GDM systems, where a high flow variation is observed. However, other water-powered chlorinators were not considered in this thesis because they require a medium level of skills for maintenance and are thus not suitable in a context where the water treatment system is operated by rural communities in Uganda. With the last category, diffusion chlorinators, water gets chlorinated through contact with solid or powdered chlorine. Since these devices are easy to operate and can be applied for intermittent flow rates, they seemed to be promising for the study area of this thesis. In the following, some of the diffusion chlorinators that were already tested in a context similar to the one of this study, are presented.

1.4.1 Tablet Feeders

There are different, suitable tablet feeders for low-income countries such as the in-line PVC chlorinator, the PurAll device, the Klormann tablet doser, or Norweco chlorinators. Although there are minor differences between these devices, the fundamental concept remains the same: The water flowing through the device comes into contact with a chlorine tablet stored in the cartridge and gets chlorinated in the process. A higher flow leads to a higher water level inside the cartridge resulting in a bigger chemical surface exposed to water. Thus, the dose should remain relatively constant despite the variation in the flow rate (EASOL, 2019). The dosing is regulated differently for different tablet feeders. One way to adjust the dosing is varying the amount of water flowing through the bypass pipe (EASOL, 2019) as done with the PureAll device (see Figure 2). One issue of this device is that the whole cartridge has to be replaced when the chlorine tablets are used up. In the case of the PurAll, the cartridge costs USD 12 and it has to be purchased from India (S. Khanzode, personal communication, January 15, 2019). Research conducted in Panama concludes that the PVC chlorinator is an effective technology that uses local materials to provide safe drinking water in rural areas. Nevertheless, FRC concentrations have to be tested iteratively until a sufficient level is reached (Orner, Calvo, Zhang, & Mihelcic, 2017). Henderson, Bradley Sack, & Erick (2005) reported that 90% (n=196) of the samples chlorinated with a tablet feeder and taken at the water storage tank showed adequate chlorination levels. However, only 31% of the samples at the households, located the furthest away in the water distribution system, had high enough FRC levels.

Figure 2: PurAll (EASOL, 2017)

1.4.2 Aquatabs Flo©

Aquatabs Flo© is a simple plastic device which is based on the dissolution of the chlorine tablets through the flow of water, whereby the dosing can be adjusted via a screw (Medentech, 2019). It was designed to be installed at an inlet to a clean water tank and was successfully implemented this way in a rural area in Nepal, for instance (L. Dössegger, personal communication, January 15, 2019). For the study site of this thesis, this configuration does not work because the inlet of the membrane tank is not at the top of the tank. Huonder (2017) pointed out – in a study where the device was installed at the taps of the water kiosks (see Figure 3) – that these devices come with rather high costs due to a short lifetime. First, they are fragile and get damaged easily seeing as they are also directly exposed to people. Second, the whole device has to be replaced when all of the tablets inside the cartridge have been dissolved.

Figure 3: Aquatabs Flo© (Huonder, 2017)

1.4.3 Dosage Float

As illustrated in Figure 4, a dosage float is a plastic device – usually used for the chlorination of swimming pools – floating in the water while the chlorine tablet inside dissolves. The dosage float was tested at a GDM water kiosk in the study area of this thesis (Busime), whereby it was placed inside the clean water tank (Huonder, 2017). A serious issue related to this set-up is the contingency of continuous chlorine presence in the membrane tank resulting in severe damage to the membranes. To address this major concern, a flow restriction device, preventing chlorinated water from flowing back to the membrane tank, was installed in the pipe connecting the membrane and the clean water tank. This device, however, impaired the already low flow rate at the water kiosks leading to unacceptable waiting times for the customers (L. Dössegger, personal communication, June 5, 2018).

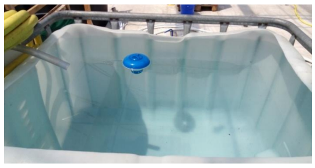


Figure 4: Dosage float (Huonder, 2017)

1.4.4 Selection of a Suitable Automatic Chlorination Device

All of the diffusion chlorinators presented above are designed to be installed before or inside a clean water tank. The advantage of this design is that variations in the dosage average out in the tank for small volumes (Y. Crider, personal communication, February 28, 2019). Additionally, this tank conveniently acts as the contact tank in which the water is retained for the necessary period of time to guarantee that the contact between water and chlorine is sufficient to destroy any pathogens (Skinner, 2001b). A disadvantage is that more chlorine is needed compared with the installation directly upstream of the taps because chlorine decays in the tank. Also, there is the risk of chlorinated water flowing back to the membrane tank, resulting in damage of the membranes. Therefore, in this study, it was planned to adjust one of the devices such that it can be applied after the clean water tank. Previous experiments with the dosage float at the GDM water kiosks in Uganda revealed that the costs of the device seem promising, which is crucial for an implementation in this region where the monthly income per household is around 78’400 UGX (USD 21) (Peter-Varbanets et al., 2017). Thus, it was decided to develop the dosage float to a Chlorine Dosing Bucket (CDB) and to evaluate its performance. So far, no automatic chlorination devices suitable for GDM systems in Uganda have been found. Therefore, this study focuses on the automatic chlorination devices Venturi and the CDB and whether they achieve adequate chlorination at GDM water kiosks in Uganda.

2 Scope and Objective

The hypothesis and the two sub-hypotheses of this thesis are as follows:

Automatic chlorination devices achieve adequate chlorination at GDM water kiosks in Uganda.

- *The 'Venturi' achieves adequate chlorination at GDM water kiosks in Uganda.*
- *The 'Chlorine Dosing Bucket (CDB)' achieves adequate chlorination at GDM water kiosks in Uganda.*

The subsequent research steps will be addressed in order to test both sub-hypotheses:

1. Can the chlorination devices 'Venturi' and 'CDB' be installed in Uganda after GDM filtration?
2. Do these devices provide a stable FRC level in the treated water provided at the tap?
3. Is the local community able to sustainably manage and operate these devices (technically and economically)?
4. Is an FRC level of 2 mg/L at the water kiosks sufficient to guarantee a satisfying quality of drinking water?
5. Regarding the taste of the water, does the local community accept FRC levels up to 2 mg/L in the drinking water?

Adequate chlorination is achieved when the research steps 1–5 can be answered positively. The first research step investigates the feasibility of the installation of the chlorination systems at GDM water kiosks. Regarding research step 2, the FRC level is considered stable when all the chlorine measurements vary around an average chlorine level and the deviation of these measurements from the average value does not exceed 1 mg/L. In this context, a sustainable application, as mentioned in research step 3, involves the following aspects: First, the local community should be able to meet the technical requirements for operation and maintenance of the chlorination devices. Second, resources such as replacement parts required for the devices have to be accessible for the locals. Third, investment and operational costs should be affordable for low-income communities. Last, the target population makes use of the chlorination devices. Research steps 4 and 5 deal with the optimal FRC level at the point of collection that is required to achieve adequate chlorination. WHO proposes dosing clear water (less than 10 nephelometric turbidity units (NTU)) with free chlorine at about 2 mg/L and twice as much if the water is turbid. These doses should ensure that an FRC level of 0.2–0.5 mg/L is maintained at all points in the distribution system and a minimum FRC level of 0.2 mg/L in stored household water (WHO, 2017a). Therefore, the goal is to establish an FRC concentration of around 2 mg/L at the water kiosks. It will be investigated if such a concentration suffices to prevent recontamination of the water after 24 h of storage (research step 4). On the other hand, since FRC changes the taste of the drinking water, it has to be clarified whether drinking water with the proposed 2 mg/L is rejected by the customer (research step 5). If chlorine levels are unacceptable to the customers, they might fall back on alternative, less safe water sources (WHO, 2017b).

The stated research steps are addressed in the subsequent chapters. Chapter 3 explains the methodology. In Chapter 4, the five main results are presented. First, issues encountered during the installation of the devices are described in Chapter 4.1. Then, in Chapter 4.2, results from the fieldwork concerning the FRC levels in the treated water provided at the tap are shown. Subsequently, the observed FRC values are compared to the theoretically expected FRC levels. In Chapter 4.3, the future sustainability of the chlorination devices by the local community is assessed. Thereafter, the results of the chlorine decay and water quality measurements are analysed (Chapter 4.4). Last, the answers from the chlorine tastings are presented in Chapter 4.5. All results are discussed in Chapter 5. Conclusions regarding the results of the presented research are drawn in Chapter 6.

3 Materials and Methods

This chapter provides an overview of the approaches and materials used. First, it introduces the context of the study. Then, the devices used for the chlorination and the chlorine measurements are explained. Subsequently, details on the data collection, the chlorine tastings, and the interviews are presented. Thereafter, the methods of data analysis are explained. Finally, the conducted calculations are outlined.

3.1 Context of the Study

The data collection for this thesis was conducted in a rural area in Eastern Uganda between October and December 2018 during the wet season. A total of five GDM water kiosks had previously been established in this area next to schools. For this study, two different types of chlorination devices were installed at three of those water kiosks. The Venturi system was tested at two recently erected water kiosks in Bulundira and Bumeru, whereas the CDB was implemented at an older water kiosk in Busime. Chlorine tastings and interviews were conducted with 48 respondents in Bulundira and 98 respondents at the older water kiosk in Bulwande. Additionally, in Lugala, 51 households participated in the chlorine tasting and interviews. These study sites are small villages with roughly 1'300 households per village. In each village, approximately 600 pupils frequent the nearby schools. The average individual lives in a radius of 1 km from the water kiosk. At most, a person would live 3 km from a water kiosk (K. Wanyama, personal communication, February 15, 2019).

3.2 Equipment and Instruments

In this chapter, the applied equipment and instruments are shown. First, the two chlorination systems Venturi and CDB are described. Thereafter, the devices used for the chlorine measurements are explained.

3.2.1 Chlorination Devices

In the following, the investigated chlorination devices are presented.

Venturi

The chlorine doser Venturi was developed by PATH, MSR Global Health, and Tufts and Stanford University, for low-resource environments. The device can be installed in-line just before a water outlet, such as a tap on a water kiosk. The device works with commonly available liquid chlorine solutions such as the 1.2% WaterGuard solution (sodium hypochlorite). Chlorine is added to the water supply with no need for electricity (MSR Global Health, n.d.). Figure 5 shows the composition of the Venturi. Liquid chlorine is filled into the chlorine tank, from which it flows into the float tank. The needle valve can be set as to allow the flow of the required amount of chlorine into the Venturi restriction at the tube, where the water flows. Since the water passes from a larger to smaller section, the flow velocity increases while the static fluid pressure decreases. This mechanism is known as the Venturi effect and is based on the fluid continuity principle and Bernoulli's principle (Scheaua, 2016). Eventually, the difference in the upstream pressure and the pressure at the constriction causes the chlorine to be sucked in. Thus, the device draws in chlorine according to the flow rate, a process that ensures the correct dosing of the water (SWAP, 2017).

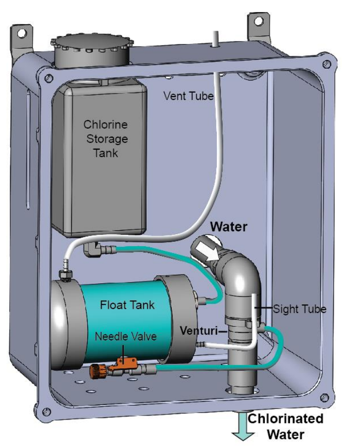


Figure 5: Composition of the Venturi (Powers et al., 2019)

Chlorine Dosing Bucket (CDB)

A prototype of the CDB was developed in the laboratory at Eawag (see Figure 6a). The device was tested in the laboratories of Eawag previous to this thesis. However, the field study presented in this thesis was the first implementation of the CDB in its intended environment. The CDB consists of a bucket with a volume of 30.4 L and two pipes. The main pipe ensures the inflow of water into the bucket, whereas the second pipe allows water to bypass the bucket. A dosage float (see Figure 6b) is fixed to the lid inside the bucket. A slowly dissolving 90% chlorine tablet (trichloroisocyanuric acid (TCCA)) of the brand Henkel was placed inside the dosage float. At the outlet of the chlorine bucket, a bent pipe is installed to prevent short-circuits and to provide a better mixing behaviour. The CDB was specifically designed to be installed at GDM water kiosks. Its intended location is downstream of the clean water tank, which contains the filtrated water but upstream of the taps.

(a) CDB

(b) Dosage float with a chlorine tablet

Figure 6: CDB and dosage float

There are three different ways of controlling the dosage. First, the valves attached to the main and bypass pipe can be opened to different degrees. Thus, one directly controls how much of the water in the device gets infused with chlorine. Second, slits at the bottom of the dosage float can be opened. To achieve maximum chlorination, four slits can be opened. Third, the number of chlorine tablets placed inside the dosage float can be varied.

3.2.2 Chlorine Measurement Devices

The acquisition of data on chlorine levels at the tap was conducted by using a portable colorimeter (LaMotte; DC1500 Colorimeter Labs, see Figure 7a) and Chlorine Diethyl-p-phenylenediamine#1 (DPD#1) RAPID Instrument Grade (LaMotte) tablets. To measure the chlorine decay and the FRC levels at the tap by the operator a pooltester (Palintest; Chlorine/pH Pooltester Kit SP610, see Figure 7b) with DPD#1 (Palintest) tablets was utilised in addition to the colorimeter.

(a) Colorimeter (LaMotte, 2019)

(b) Pooltester (Hygiene4less & Maclin Group, 2019)

Figure 7: Chlorine measurement devices

Colorimeter

The colorimeter has a measuring range from 0 to 4.0 mg/L, which can be extended by dilution. It measures among others the FRC concentration expressing the values in parts per million (ppm), which corresponds to mg/L. For measuring the FRC levels with the colorimeter in the field, a standard procedure was applied. First, a clean tube was rinsed with sample water and then filled with 10 mL of sample water. The tube was capped, wiped dry, and inserted into the chamber to scan a blank of the sample. It was removed from the colorimeter and a Chlorine DPD#1 Instrument Grade Tablet was added. The FRC reacted instantaneously with the buffered DPD indicator and generated a pink-red colour, the intensity of which proportionally correlates with the amount of chlorine present (LaMotte, 2015). The tube was capped, shaken for 10 s, turned on its head slowly 5 times, and immediately inserted into the chamber to scan the FRC concentration.

Pooltester

In addition to the colorimeter, a pooltester was required to measure the chlorine decay for two reasons: First, the FRC concentration in the jerry cans after 24 h had to be measured simultaneously at different locations. However, only one colorimeter was available. Second, instrumental tablets needed for the colorimeter were not sufficiently available in Uganda. Thus, the FRC levels in the jerry cans after 30 min were also measured using a pooltester to economise on the instrumental tablets. To measure chlorine concentration with the pooltester, first, any colour deposits were removed. If the sample was taken from the tap, the water was run for 3 s before the tube was filled repeatedly three times to remove any chlorine deposits. If the sample was taken from the jerry can, the container was stirred to mix the water before the tube was filled and emptied 3 times with drinking water. In both cases, the pipe was filled to capacity with sample water and one DPD#1 tablet was added to the sample. The pooltester was shaken well until the tablet dissolved completely. The FRC reacts with the DPD #1 tablet to produce a pink-red colour. The colour intensity again indicates the FRC levels in the water (Palintest, 2016). After 30 s, the colour intensity of the water sample was compared to the calibrated colour chart. Reliance on visual interpretation when differentiating between similar colour intensities can result in significant measurement errors.

3.3 Study Design

In the following, the design of the study is outlined. First, the frequency and procedure of the data collection in the field is explained. Both the chlorine measurements and the water quality measurements are described. Subsequently, the process of the chlorine tastings and interviews is presented.

3.3.1 Chlorine and Flow Rate Measurements

Chlorine levels were measured at the two different water kiosks with the installed chlorination devices. In parallel, flow rates of the water at the taps were assessed by recording the time requirement to fill a 20 L jerry can. In Busime, the total flow rate corresponds to the sum of the individual measured flow rates at each tap where water was flowing. Additionally, pH and temperature of the water samples were assessed with a pH indicator strip and a thermometer, respectively. Data on chlorine concentration is collected to address research steps 1, 2, and 4 as stated in Chapter 2. First, chlorine levels were measured at the taps of the water kiosks with a colorimeter to check if the devices were successfully installed (research step 1). A successful installation also required the implementation of a dosing set-up which ensured FRC values in the required range of around 2 mg/L. Thereby, in the case of the Venturi six different needle valve positions were tested on six days within two weeks. In the case of the CDB, four different valve settings were investigated on three consecutive days and four different degrees of slit openings on two consecutive days. As depicted by Table 1, the chlorine measurements to assess the installation process including the dosing set-up were taken on 31 days within around 1.5 months every 15 min for 2–5 h.

Second, chlorine data was collected at the taps of the water kiosks with a colorimeter to assess the FRC levels in the treated water provided at the tap over a short and a longer period (research step 2). Table 1 shows the frequency of these measurements. In the case of the Venturi, FRC concentrations were measured every 15 min over a duration of 3 h to determine the FRC levels in the treated water provided at the tap over a short period. During the entire period of 3 h, the tap was kept open to allow a constant flow of water. Every 30 min, flow rates were measured. Additionally, the amount of water used each hour, displayed by the water meter, and the chlorine level in the chlorine tank of the Venturi were recorded by the author. These two parameters were used to calculate the amount of chlorine required to treat 1 m^3 of water. This information was necessary to later quantify the operational costs of the Venturi (see Chapter 3.5). Moreover, on 9 days within a period of 12 days, FRC concentrations were measured every 15 min for 1 h in Bulundira. The flow rate was assessed once a day.

Table 1: Frequency of the FRC measurements conducted to assess the installation process and the FRC levels in the treated water provided at the tap

	(1) Installation process		(2) FRC levels			
	Longer period		Short period		Longer period	
	Bulundira	Busime	Bulundira	Busime	Bulundira	Busime
Number of measurement days	18 d	13 d	1 d		9 d	23 d
Measurement period	44 d	32 d	1 d		12 d	27 d
Time intervals	15 min		15 min		15 min	
Measurement duration per day	2–5 h		3 h	6 h	1 h	

In the case of the CDB, FRC concentrations were measured at the taps every 15 min for 6 h on one day. In the beginning, only one tap was running for 30 min. Then all three taps were opened for 1 h. Thereafter, just one tap was running for 1 h, and the rest of the time all three taps were turned on again. Flow rates were assessed each hour at the running taps. Second, FRC concentrations were measured on 23 days at the taps. On 17 days, the operator from the water kiosk in Busime measured the FRC concentrations and flow rates with a pooltester 3 times per day from the first tap at the water kiosk: one in the morning, one at midday, and one in the evening. On the other six days, the FRC concentrations were measured by the author of this thesis. These measurements were conducted every 15 min for 1 h. At the beginning of these measurements, usually, all three taps were running and, in the end, only one tap. On these days, the flow rates were assessed as well: once with three running taps and once with only one running tap.

Last, data on chlorine levels were collected to address research step 4. The author was primarily interested in the degree to which chlorine decayed within 24 h and if the two different devices would lead to different decay rates. The chlorine decay was assessed in 46 jerry cans in Bulundira, 21 jerry cans in Busime and 48 jerry cans in Bumeru. Jerry cans were randomly chosen from the customers of the water kiosks who have provided informed consent. FRC levels were measured with a colorimeter or a pooltester 3 times in the jerry cans. The water containers were thoroughly shaken to ensure a uniform chlorine concentration. The first FRC measurement was conducted directly after the jerry cans were filled with drinking water from the water kiosk. The second and third measurements were taken after 30 min and 24 h $\pm$ 3 h, respectively. The people were advised to leave some water in the jerry cans when they returned the next day to allow the measurement of the FRC level after 24 h. Few participants did not follow this instruction. The samples of those participants were excluded from the study.

3.3.2 Water Quality Measurements

The microbial quality of the water stored in the jerry cans for 24 h was investigated. These measurements permit the comparison of the water quality after 24 h of storage with the FRC concentration after 24 h. This allows a conclusion regarding the minimum remaining chlorine level required after 24 h to sustain satisfying water quality.

Eleven jerry cans were tested in Busime, 46 in Bulundira and 48 in Bumeru. These measurements were done twice: once at the water kiosk and once 24 h later at the households. The jerry cans were randomly selected from all current water kiosk customers that have provided informed consent of participation.

Before collecting the data on water quality, the author of this thesis disinfected her hands and let the taps run for 5 s. Thereupon, water was sampled in 100 ml sterile Whirl-Pak Bags (Nasco, Whirl-Pak® Write-On Bags – 4 Oz. (118 mL)). If the water was chlorinated Whirl-Pak Thio-Bags (Nasco, Whirl-Pak® Thio-Bags® – 4 Oz. (100 mL)) were used. Before taking the samples from the jerry cans, the containers were well shaken. The samples were stored in an icebox and the water quality of these samples was analysed in the evening of the same day. The best practice to verify the microbial quality of drinking water is testing of *Escherichia coli* (*E. coli*). *E. coli* is a bacteria that serves as an indicator for faecal contamination (WHO, 2017a). Thence, the samples were tested on *E. coli* and total coliforms. To analyse water quality with the method of membrane filtration, first, the whole filtration device including the connecting tubes was boiled to ensure disinfection. Later, the 100 ml water samples, which were stored in ice chests, were vacuum filtered through 0.45 μm cellulose membrane filters (Merck, S-Pak Filters 0.45 μm, 47 mm white gridded). Then, by using a sterilised tweezer, the filters were placed on CompactDry "Nissui" EC Plates (Nissui Pharmaceutical CO., LTD), which were incubated at 35–37 °C for 24 h. After 24 h of incubation, the *E. coli* and total coliform colonies were counted visually up to 2’000 colony-forming units (CFU) per plate. When electricity was not available, incubation was achieved by using body temperature instead of conventional incubation. For this purpose, the plates were placed into a thin bum bag which the author carried closely during 24 h.

3.3.3 Chlorine Tastings and Interviews

Chlorine tastings were conducted to identify acceptable FRC levels by the local community given its detrimental impact on taste. After participating in the chlorine tastings, the respondents were questioned about their opinions on chlorine. Additionally, in Busime and Bulundira the residents were requested to provide their views on the chlorination devices. At these study sites, interviews with the operators were conducted to assess the feasibility of the operation of the chlorination devices by the local community. The interviews with the operators were undertaken at the end of the field study after the operators were already accustomed to the handling of the devices. Table 2 gives an overview of the chlorine tastings and interviews including the number of participants.

All households that frequented the water kiosks during the study period and provided informed consent were included in the study. From each household, the person responsible for drinking water and hygiene was interviewed. In most cases, this was the wife. The interviews and chlorine tastings at the first study site (Lugala) were conducted at the households. In contrast, all other interviews were run inside the water kiosk buildings. To avoid social influence from other individuals, each participant had to enter the kiosk building alone. The interviews and chlorine tastings were supported by a translator who spoke the local language. In a first step, the translator explained the goal and procedure of the interview. Thereafter, the participants were asked to assess the taste of the different samples. From each sample, 10 mL of water was collected inside a plastic cup. The samples given to the participants contained the following amounts of chlorine: 0 mg/L, 0.5 mg/L, 1 mg/L, 1.5 mg/L and 2 mg/L. It was decided to try an additional sample with 4 mg/L chlorine at the chlorine tastings in Bulundira and Bulwande. This sample with a high chlorine concentration should act as a test to show if the participants assessed the taste logically. The solutions were handed out in ascending chlorine concentration starting with 0 mg/L. To assess the taste acceptability, the participants were asked to rate the taste of each sample. After the chlorine tasting the participants were questioned about their opinions on chlorine. The answers from all the interviews and the chlorine tastings were recorded on a tablet using digital questionnaires on the Open Data Kit (ODK) Collect app (Open Data Kit, 2017). Data was read out into Excel.

Table 2: Overview of the undertaken chlorine tastings and interviews

Study site	n	Content
Lugala	51	Interviews on the acceptance of chlorine & chlorine tastings
Bulundira	48	
Bulwande	52	
Bulwande (children)	46	
Bulundira	48	Interviews on the acceptance of the chlorination devices
Busime	28	
Bulundira	2	Interviews on the acceptance of the chlorination devices by the operators
Busime	1	

In the following, the procedure of the preparation of the chlorine samples is described. At the first study site (Lugala), the chlorine solutions were prepared in the morning in the laboratory. A pretest showed that over the course of 3 h the concentration of FRC decreased by around 0.2 mg/L when the water was held in closed bottles and stored in the shadow. The chlorine tastings took place around 3 h after the preparation. Therefore, the chlorine solutions were prepared with an FRC level that was 0.2 mg/L above the target value. With a syringe, 1 mL of 1.2% liquid chlorine from the brand Waterguard was injected into a bottle containing 1 L of bottled drinking water. This resulted in a liquid mixture with 12 mg/L chlorine. The bottle was well shaken. After 30 min, to allow for sufficient contact time, a specific amount of this mixture was injected with a 100 mL syringe into four bottles. These bottles already contained 500 mL of bottled water. The specific amounts of liquid mixture required for the four different chlorine solutions can be found in Table A.1 in the Appendix. The preparation of these chlorine solutions in the morning took approximately 1.5 h. Additionally, around 100 Chlorine DPD#1 Instrument Grade Tablets were used for the eight chlorine tastings in Lugala. To save time and tablets, it was decided to do the two remaining chlorine tastings on two single days at the water kiosks. This time, the chlorine solutions were prepared directly at the water kiosks with bottled water in large buckets. For the different chlorine solutions, a specific amount of 1.2% liquid chlorine from the brand Waterguard was injected with either a 1 or 5 mL syringe into the buckets containing each 8 L of bottled water. The specific amount of chlorine solution used is listed in Table A.2 in the Appendix. Since chlorine is volatile once it is exposed to air (WHO, 2017b), the buckets were closed with lids.

3.4 Data Analysis

An independent t-test was conducted to check whether there is a statistically significant difference in the decay rate of the chlorine tablet and the liquid chlorine during the time period of 0.5 h and 24 h after filling the jerrycans. The differences in the chlorine decay rates are normally distributed. Levene's test is non-significant ($p = 0.759$). Thus, it is assumed that the two chlorine forms have an equal variance in the chlorine decay. Therefore, the assumptions for an independent t-test are met. Partial correlation was applied to investigate the correlation between the FRC values and the number of *E. coli*. The Spearman correlation coefficient (two-tailed) instead of the Pearson correlation coefficient was used because the *E. coli* data are not normally distributed. Since data for the flow rates and FRC concentrations in Busime and Bulundira are normally distributed, the Pearson correlation coefficient (two-tailed) was used to explore the correlation between the FRC values and the flow rates occurring at the water kiosk in Bulundira over 3 h and at the water kiosk in Busime over 4 weeks. QQ-plots and the Kolmogorov-Smirnov and Shapiro-Wilk tests were used to test if a distribution is normal.

3.5 Calculations

First the development of the theoretical model for the mode of operation of the CDB is explained. Subsequently, the calculations to quantify the costs of the chlorination devices and the disinfection efficiency are shown.

3.5.1 Theoretical Aspects

The intention of the author of this thesis was to build a theoretical model for the mode of operation of the chlorination devices, which helps improve the performance of the chlorination systems. In the case of the Venturi, a quantitative statement was not possible. Therefore, the theoretical basis of the Venturi principle was qualitatively outlined. For the CDB, a model was established based on the mass balance of the chlorine concentration inside the chlorine bucket (Equation 1). Thereby, the chlorine bucket is approximated by an ideal completely mixed batch reactor (CMBR)[1] (Crittenden et al., 2012). The dissolution of the chlorine tablet (second last term in Equation 1) was modeled as a reaction where the reaction rate decreases over time due to saturation of the water with chlorine. The chlorine decay due to reactions with dissolved components present in the water (last term in Equation 1) was modeled as a first order reaction based on results of previous studies (Crittenden et al., 2012).

$$V * \frac{dC_1}{dt} = Q_1 * C_{\text{in}} - Q_1 * C_1 + K * (K_{\text{So}} * IAP)^{\text{n}} * V - k_{\text{decay}} * C * V \quad (1)$$

where V = volume of the chlorine bucket, C_1 = chlorine concentration inside the bucket, Q_1 = flow rate to the chlorine bucket, C_{in} = chlorine concentration in the water flowing to the bucket, K = constant, K_{So} = solubility constant, IAP = ion activity product, k_{decay} = decay rate of chlorine

The solubility constant for the TCCA tablet at 25 C° is 12 g/L (International Labour Organization, 2007), whereas the chlorine concentrations in the chlorine bucket were in the range of 0.7–4.1 mg/L. Since the ion activity product is around three orders of magnitude smaller than the solubility constant of the tablet, the ion activity product could be neglected. If n is assumed to be one, Equation 1 can be written as presented in Equation 2. At a later stage, the fitting of the modeled values to the measured ones with different values for n indicated that a value of one was a good assumption for n. In Equation 2, the reaction order of the dissolution of the chlorine tablet follows a zero order, which was also confirmed in a batch experiment. In this experiment, also the dissolution rate of the chlorine tablet for a slit opening of 30% and 50% was determined.

$$V * \frac{dC_1}{dt} = Q_1 * C_{\text{in}} - Q_1 * C_1 + k_{\text{dissolution}} * V - k_{\text{decay}} * C * V \quad (2)$$

where $k_{dissolution}$ = dissolution rate of chlorine tablet

For the batch experiment a chlorine tablet was put inside the dosage float while once 30% and once 50% of the slits were open. The dosage float was placed in a bucket with tap water. FRC levels were quantified with a colorimeter at different points in time. Time versus the measured FRC values was plotted (see Figure A.1 and Figure A.2 in the Appendix). The data points of the graphs correspond to a straight line. This indicates, as explained in Crittenden et al. (2012), that the dissolution of the chlorine tablet follows a zero-order reaction. The decay rate of chlorine (k_{decay}) was determined by fitting the steady state FRC concentrations calculated with Equation 2 to the FRC concentrations measured in the field. Thereafter, the fitted decay rate of the chlorine inside the bucket was compared to the observed chlorine decay in the jerry cans.

[1]The following assumptions are made for an ideal CMBR: (1) the contents of the tank are completely uniform with no density gradients or dead space, (2) the probability of a particle of water to be in any part of the tank is follows a uniform distribution, (3) throughout the reactor, the temperature is uniform, (4) a chemical added to the reactor is instantly and uniformly distributed (Crittenden et al., 2012).

3.5.2 Financial Viability

Equation 3 reflects the quantification of the total costs *(TC)* of treating 1 m^3. The total costs include the investment costs per device *(IC)* and the operational costs of 1 m^3 of treated water *(OC)*. According to MSR Global Health (n.d.), the Venturi has a lifetime of 10 years and the same lifetime was assumed for the CDB. The total costs of purchasing the monthly water amount from the water kiosk per household were also set in relation to its average income.

$$TC = \frac{(IC + OC * V_{\text{year}} * t)}{V_{\text{year}} * t} \tag{3}$$

The investment costs *(IC)* represent the initially required expenditures for the devices. This information was provided by its developer, MSR Health, in the case of the Venturi. For the compositions of the CDB, prices in Uganda were considered. The volume of water *(V_{year})* is the yearly amount of water sold on average at the water kiosks. This value was obtained by averaging over 3 years at Busime and over 6 months at Bulundira based on data collected from the functionality tool provided by the organisation African Water Solutions. The time scenarios (t) 3, 5, and 10 years were chosen. This variable represents the times over which the investment costs are spread.

Operational costs of the Venturi *($OC_{Venturi}$)* were calculated according to Equation 4. The price per bottle of liquid chlorine bought at a supermarket in Busia in Kenya was used for the purchasing costs *(PC_{bottle})* of one chlorine bottle. The value for the number of bottles required for treating 1 m^3 of water *(N_{bottle})* was based on observations regarding the chlorine amount required to treat different amounts of water. The amount of chlorine needed to treat 1 m^3 of water was estimated using ordinary least squares (see Figure A.3 in the Appendix).

$$OC_{\text{Venturi}} = PC_{\text{bottle}} * N_{\text{bottle}} \tag{4}$$

For the CDB, the operational costs *(OC_{CDB})* were assessed according to Equation 5. The information for the purchasing costs of one Henkel chlorine tablet *(PC_{tablet})* was provided by a supplier located in Kampala. The time needed for the entire dissolution of one chlorine tablet ($t_{\text{dissolution}}$) was calculated with the help of the experimentally determined dissolution rate of the tablet. The flow rate was estimated by regressing the measured FRC on the flow rate (see Figure A.4 in the Appendix).

$$OC_{\text{CDB}} = \frac{PC_{\text{tablet}}}{t_{\text{dissolution}} * Q} \tag{5}$$

3.5.3 Efficiency of Disinfection

The efficiency of disinfection was calculated by multiplying the residual chlorine concentration observed after the contact time with the contact time (Crittenden et al., 2012). To determine the Ct values for the CDB for different flow rates, the FRC concentrations inside the chlorination bucket were multiplied with the corresponding hydraulic residence times. The FRC concentration inside the bucket was calculated by dividing the measured FRC levels at the taps by 0.75, which is the share of water that flows to the bucket. The hydraulic residence time corresponds to the volume of the chlorination bucket divided by the observed flow rate through the bucket. In the case of the Venturi, the contact time required to achieve a Ct value that is needed to achieve 4-log inactivation of viruses and 3-log inactivation of Giardia cysts was quantified. Thereby, it was calculated with an FRC concentration of 1.2 mg/L, which is the average FRC level observed 30 min after having filled the jerry cans with the chlorinated water.

4 Results

This chapter shows the results of the evaluation of the two automatic chlorination devices for GDM water kiosks in Uganda. It begins with the issues encountered during the installation of the chlorination systems (Chapter 4.1). In Chapter 4.2, the FRC levels in the treated water provided at the tap are shown. Subsequently, the sustainability of the application of the chlorine systems is outlined (Chapter 4.3). Finally, the last two chapters provide an evaluation of a suitable FRC level in the treated water at the GDM systems. Thereby, Chapter 4.4 presents the results of chlorine decay and water quality. The answers regarding the taste acceptability of chlorine solutions obtained in chlorine tastings are presented in Chapter 4.5.

4.1 Installation of the Venturi and CDB

This chapter gives an overview of the installation issues and the necessary adjustments. Both automatic chlorination devices could be installed at the GDM systems. It nevertheless took around 1.5 months to successfully complete the installation of the devices including finding a suitable chlorine dosing set-up due to complications occurring during the installation process.

4.1.1 Venturi

The plan was to install one Venturi at the water kiosk in Bumeru and the other one at the water kiosk in Bulundira. In Bumeru, the Venturi could not be installed successfully, as no chlorine flow between the chlorine tank and the injection point could be established. Most likely, air bubbles obstructed the passage inhibiting the chlorine flow. No such problems occurred with the Venturi in Bulundira. As shown in Figure 8a, initially, the Venturi was installed inside the water kiosk building at the main pipe in Buldundira. Like this, one Venturi sufficed to chlorinate four taps and the customers can neither see nor touch the chlorination device. Nevertheless, each time the taps were closed water accumulated in the chlorine tank. As a result, the chlorine concentration inside the chlorine tank became diluted. To counteract, one tap was dismantled ensuring the outflow of water from the pipe when there was a water stop.

(a) Initial installation (inside the water kiosk)

(b) Final installation (outside the water kiosk)

Figure 8: Venturi installed at the water kiosk in Bulundira

Another issue was the distance between the chlorine injection point inside the Venturi and the outlet of the water. The device was designed for a distance of 8–10 cm (L. Klein, personal communication, October 25, 2018), whereas the actual length was 38 cm in Bulundira. At lower flow rates, the difference in height between the injection point and the outlet, and not the rate of the flow, mostly drives the dosing. This means that the larger the distance between the injection point and the outlet, the higher the chlorine dosing (L. Klein, personal communication, October 25, 2018). As a consequence, high FRC values were observed at lower flow rates. Thus, the outlet tube was shortened to a length of 8 cm. But even with this adjustment, the Venturi did not dose reliably, because the Venturi was designed to be directly upstream of the water outlet. Thus, any obstacle downstream of the Venturi, even just an elbow in the pipe, causes enough back-pressure to result in under-dosage (L. Klein, personal communication, October 25, 2018). Therefore, the Venturi was installed directly before the tap (see Figure 8b), only serving one outlet instead of four as in the previous set-up. The operator was requested to close the other three taps where no chlorine was injected for the duration of the study. The needle valve of the Venturi was set to 9.75 for the final dosing set-up. The needle valve, which acts as a flow restriction, can be fixed to a value between 0 and 10. The higher the number, the less the flow is restricted and thus the higher the chlorine dosing.

4.1.2 CDB

As depicted in Figure 9a, the CDB was installed downstream of the container holding the treated water (clean water tank) but upstream of the taps at the water kiosk in Busime. Figure 9b shows a schematic representation of the CDB, which helps to understand the following statements.

(a) (i) lake tank, (ii) membrane tank, (iii) clean water tank, (iv) CDB, (v) taps

(b) Representation of CDB

Figure 9: Water kiosk in Busime with installed CDB

The first problem encountered during the installation process was the continuous dosing of the chlorine tablet. Constant exposure of the tablet to the water led to elevated FRC concentrations when no water outflow occurred for an extended period of time, for example overnight. Constant contact with the water occurred because the chlorine bucket was always filled to capacity when the water outflow was stopped at the taps. Thus, the mechanism was adjusted to prevent dosing at times when no water was distributed at the taps. By attaching the dosage float to the lid of the CDB, contact of the chlorine tablet with the water is avoided when dosing is not desirable. The operator had to close the main valve at times when no water was fetched by the customers. The main valve was located between the clean water tank and the CDB. By dismantling one of the taps, water was allowed to flow out of the bucket when the main valve was closed. Conveniently, one of the taps was already leaking, creating the desired effect without dismantling any infrastructure. Yet, due to the airtight design of the bucket, which was intended to prevent an uncontrolled outflow of water, no water left the bucket even through the leaky tap. Therefore, a tube that introduced atmospheric pressure to the bucket was installed to balance internal and atmospheric pressure. This ensured the outflow of water from the bucket. The water that left the bucket after the main valve was closed usually carried FRC levels above 4 mg/L. Therefore, the operator was advised to use this water (around 10 L) for cleaning.

The height at which the CDB was installed played a crucial role in the functioning of the device. First, the bucket should be placed so that the top of the bent tube, which is located inside the chlorine bucket at the outlet (see Figure 9b), is below the level of the outlet of the clean water tank. Otherwise, a small amount of water in the clean water tank would cause the water level in the chlorine bucket to drop below the bent tube. Consequently, the chlorinated water inside the bucket would not flow out and the water at the tap would not be chlorinated. Second, the top of the bent tube should be placed above the height of the taps. The water level inside the chlorine bucket will naturally equate with the placement of the taps when the inflow of water is interrupted. Thus, if the CDB is installed too low, the water does not flow out of the bucket when the main valve is closed. To stop the chlorine dosage when the water inflow is interrupted, the water level should drop at least to the top of the bent tube.

Field measurements gave the impression that the operation of the valves, which control the water flow to the bucket and to the bypass pipe, had only an effect on the FRC values in the short term (< 30 min). Therefore, it was assumed that the operation of these valves cannot be used as a dosing option. The valve to the bucket was opened 75% and the valve to the bypass pipe 25%. It was not necessary to vary the amount of chlorine tablets inside the dosage float because adjusting the degrees of slit openings at the dosage float already ensured dosing in the required range. As a final dosing set-up a slit opening at the dosage float of 30% was applied.

4.2 FRC Levels in the Treated Water Provided at the Tap

This chapter deals with the FRC levels created at the water kiosk taps. First, the results of the data on FRC levels collected during the field study are shown. Second, the empirical data is compared with theoretical values.

4.2.1 Field Measurements

Subsequently, the FRC levels and flow rates measured at the taps of the water kiosks are illustrated both for the Venturi and the CDB. Each data point reflects one measurement. First, the results over a short period and then the results over a long period are shown.

Venturi

The flow rate and the average FRC concentration caused by the Venturi and measured at the taps are illustrated by Figure 10. During the 3 h measurement period, the water was constantly flowing from the tap resulting in a decrease in the flow rate from 20 to 14 L/min. The level of FRC ranged from 1.7 to 2.6 mg/L, and was significantly correlated with the flow rate ($r = -.845$, $p < .05$).

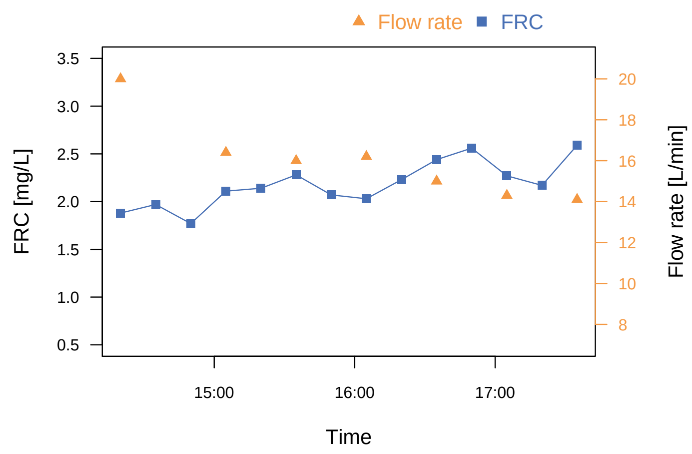


Figure 10: FRC measured at the tap with Venturi over 3 h

Figure 11 presents the flow rate as well as daily minimum and maximum FRC concentrations, for a period of two weeks at the tap with the Venturi. The minimum and maximum chlorine concentrations range from 1.8 to 2.6 mg/L and from 2.4 to 3.3 mg/L, respectively. The average values oscillate around a chlorine level of 2.5 mg/L. Nonetheless, FRC values above 5 mg/L were observed, when the flow rate at the tap decreased to a value below 6 L/min.

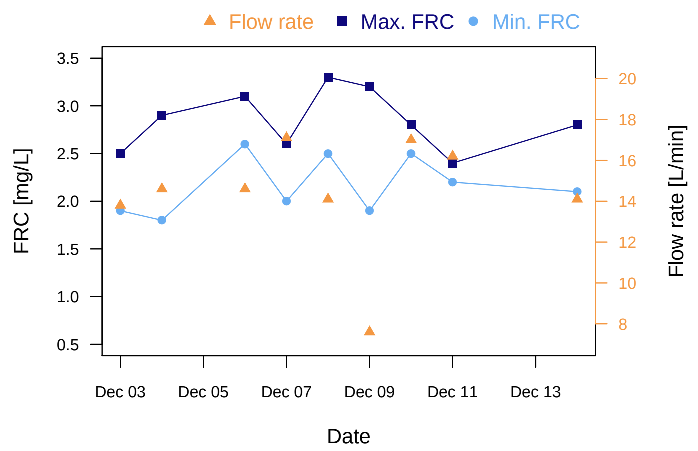


Figure 11: FRC measured at the tap with Venturi over two weeks

CDB

As illustrated in Figure 12, the FRC values observed at the tap with the CDB over a period of 3 h range from 1.7 to 3.1 mg/L. The measured flow rates in the same time period remained almost constant at 4 L/min. In the case of the CDB, the flow rate represents the total flow rate, which is the sum of the individual flow rates measured at each tap where water was flowing.

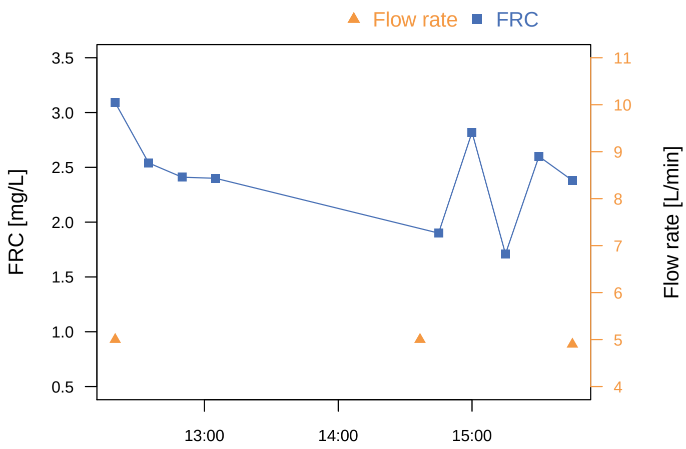


Figure 12: FRC measured at the tap with CDB over 3 h

Figure 13 shows the flow rate and the band of FRC levels, bordered by the minimum and maximum levels, for a period of four weeks at the tap with the CDB. There is a high variation in the minimum (from 0.3 to 2.3 mg/L) and the maximum chlorine concentrations (from 0.5 to 3.1 mg/L). The FRC values, which were measured at the same time as the flow rates, were significantly correlated with the flow rates ($r = -.900$, $p < .01$). High FRC values (∼2.5 mg/L) occur at low flow rates (∼4 L/min) as observed from November 23 to 30. In contrast, the high flow rates (∼10 L/min) present from December 14 to 21 result in low FRC levels (∼1 mg/L). From November 28 to December 5 there was almost no water in the clean water tank because the pump did not work. Only on December 3 water was available due to heavy rains.

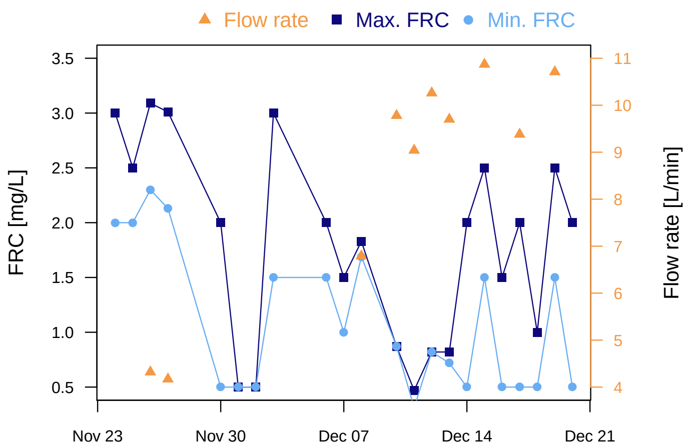


Figure 13: FRC measured at the tap with CDB over four weeks

4.2.2 Theoretical Aspects

In this chapter, the theoretical basis of the mechanism underlying the chlorination devices is presented. The goal was to develop a model with which the empirical FRC values can be compared to the theoretical figures. In the case of the Venturi, no model could be developed. Thus, the mode of operation of the Venturi is only discussed qualitatively. For the CDB, a model to predict FRC values was established. Further, the alignment of the theoretical and empirical data is evaluated. Last, it is demonstrated how the model can be used to improve the design of the CDB.

Venturi

The Venturi effect is based on the fluid continuity principle and on Bernoulli's principle (Scheaua, 2016). In the

Venturi device the water flows from a larger *(A_1)* to a smaller Venturi section *(A_2)* with a constant volume flow rate *($A_1 * v_1$)*. Thus, the velocity of the water is increased *(v_2)*, as the water needs to flow faster in the constricted area. This phenomenon is based on the fluid continuity principle, which is shown in Equation 6 (Kleinstreuer, 2010).

$$A_1 * v_1 = A_2 * v_2 \tag{6}$$

Bernoulli's principle is presented in Equation 7 (Kleinstreuer, 2010), whereby ρ is the density of the water. Since the Venturi constriction is very short, the potential energy of a water molecule in the constriction is approximately equal to the energy of a molecule in the bigger tube. Therefore, the term for potential height (ρgh) drops out of Equation 7. If the velocity increases in the constricted Venturi area *(v_2)*, the pressure *(p_2)* has to decrease in this area to satisfy Equation 7. Eventually, the difference in the upstream pressure *(p_1)* and the pressure at the constriction *(p_2)* will cause the chlorine to be sucked into the water stream at the Venturi constriction.

$$p_1 + \rho g h_1 + \frac{1}{2}\rho {v_1}^2 = p_2 + \rho g h_2 + \frac{1}{2}\rho {v_2}^2 \tag{7}$$

CDB

Equation 8 represents the steady state solution of Equation 2 presented in Chapter 3.5. The variables for Equations 8–10 are illustrated in Figure 14 and described in Table 3. Based on Equation 9, the theoretical outflow of the chlorine concentration at the taps can be calculated. Substituting C_1 in Equation 9 (the chlorine concentration of the water inside the bucket) by the value in Equation 8 yields Equation 10.

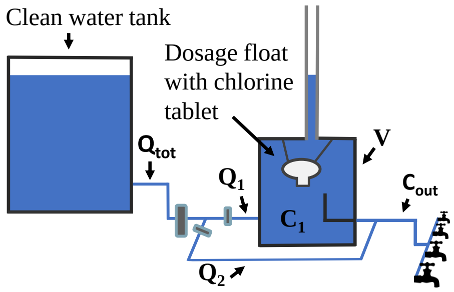


Figure 14: Representation of the CDB

Table 3: Description of variables and measured/calculated values

Variable	Description	Measured/calculated values
C_{out}	range of measured chlorine concentrations at the taps	0.5–3.1 mg/L
C_1	range of calculated chlorine concentrations in the bucket	0.7–4.1 mg/L
Q_{tot}	range of measured total flow rates	2.7–9.8 L/min
Q_1	flow rate to bucket	0.75 * Q_{tot}
Q_2	flow rate to bypass pipe	0.25 * Q_{tot}
$k_{dissolution}$	dissolution rate of the tablet per unit volume (slit opening = 30%)	0.51 mg/L.min
k_{decay}	decay rate of chlorine (fitted)	0.08 1/min
$\theta = \frac{V}{Q_1}$	range of calculated hydraulic residence times	4–15 min
V	volume of the chlorine bucket	30.4 L

$$C_1 = \frac{k_{\text{dissolution}} * V}{Q_1 + k_{\text{decay}} * V} \tag{8}$$

$$C_{\text{out}} = C_1 * \frac{Q_1}{Q_{\text{tot}}} \tag{9}$$

$$C_{\text{out}} = \frac{k_{\text{dissolution}} * V}{Q_1 + k_{\text{decay}} * V} * \frac{Q_1}{Q_{\text{tot}}} \tag{10}$$

Utilising Equation 10 and the empirical data presented in Table 3, the expected FRC levels at the taps can be calculated for different flow rates. Figure 15 compares the calculated chlorine concentrations according to Equation 10 with the empirical data on FRC levels. The model represents the measured value well for the flow rates in the middle range. For low flow rates, the modeled values underestimate the empirical values, whereas for high flow rates the modeled values overestimate the empirical values. It was found that according to the fitted k_{decay} the chlorine concentration inside the chlorine bucket decreases by 92% in 30 min. In contrast, measurements show that on average the chlorine concentrations inside the jerry cans decreased by 20% over the duration of 30 min (see Chapter 4.4).

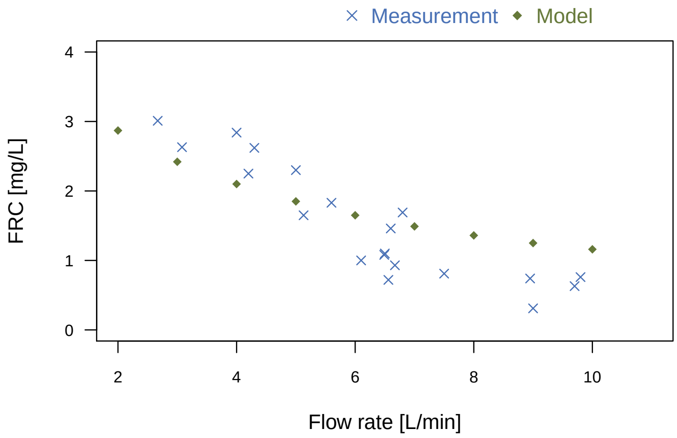
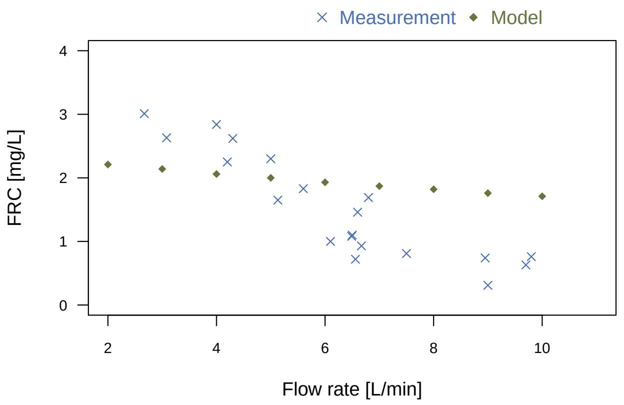


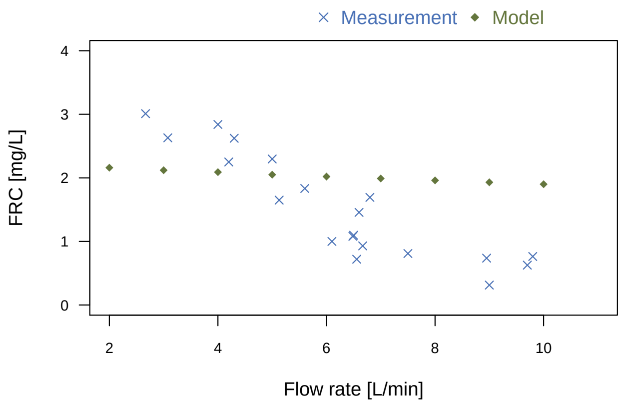
Figure 15: Calculated vs. measured FRC concentrations

The model suggests a dissolution rate of around 0.63 mg/L.min to achieve an FRC of 2 mg/L at the taps for the average observed flow rate. Since the chlorine concentration at the outflow varies significantly with the variation of the flow rate ($r = -.900$, $p < .01$), a different rate of dissolution for different flow rates would be reasonable. The rate of dissolution of the tablet can be changed by the degree to which the slits are opened. A slit opening of around 30% is required to achieve the target concentration at the outflow if the flow rate is rather low (4.5 L/min), and around 50% if it is high (8.0 L/min). This finding indicates that the FRC concentration could be kept more stable if the bucket would be equipped with two different slit openings instead of only one (see Figure B.1 in the Appendix). In practice, it implies that the operator has the task to check the volume of water inside the clean water tank every morning. If the clean water tank is less than half full, the flow rate is low. In this case, the operator could open the slit to around 30%. Otherwise, a slit opening of around 50% could be applied.

The developed model helped to come up with two further strategies to attenuate the variation in the FRC levels at the taps. Field experiments suggested that the operation of the valves, which control the water flow to the bucket and to the bypass pipe, have no effect on the FRC values in the longer term. However, it can be deduced from Equation 10 that theoretically the value of the flow rate to the bucket (Q_1) influences the FRC concentration at the tap. This indicates that the finding in the field can not be confirmed by the developed model. In fact, the model implies that a small flow rate to the chlorine bucket could theoretically result in stable FRC values at the tap. Figure 16a shows the calculated FRC values when the share of the flow rate to the bucket is reduced from 75% to 10%. Alternatively, according to Equation 10, an increase of the chlorine bucket volume would theoretically also lead to more stable FRC values. For instance, if the volume of the chlorine bucket is increased from 30.4 L to 500 L, more stable FRC levels in the water provided at the tap might be ensured by the CDB (see Figure 16b).



(a) Decreased flow rate through chlorine bucket



(b) Increased volume of chlorine bucket

Figure 16: Calculated vs. measured FRC concentrations with the application of mitigation strategies

4.3 Assessing the Sustainability of the Application

This chapter outlines the main characteristics required for a sustainable application of the chlorination devices. First, the opinions of the local operation team about operating and maintaining the devices are presented. Thereafter, the availability of a supply chain for the devices and chlorine is evaluated. Then, the investment and operation costs of the devices are compared. Last, the attitudes of the customers towards the installed chlorination systems are shown.

4.3.1 Operation and Maintenance

In Bulundira, the operator and the secretary preferred to run the water kiosk with the Venturi over solely filtrating the water. Both were convinced that chlorinated water is safer to drink compared to only filtrated water. Operating the Venturi device was easy for both operators in Bulundira. The only difficulty that arose was the addition of the correct amount of chlorine bottles. The author advised the operators to use two chlorine bottles when the clean water tank was more than half full and to use only one bottle otherwise. The operators assessed the water level in the clean water tank by knocking on the tank with a stick. However, the operator argued that the quantity of chlorine he had to put inside the device did not correspond to the amount of water in the clean water tank. Hence, he always applied two bottles of liquid chlorine regardless of the water level in the clean water tank. They did not wish for any improvements in the current system except that all the four taps instead of only one tap should be operable. They argued that with this set-up, the customers would be able to choose between chlorinated and unchlorinated water. Further, it would take less time to fill the jerry cans. They reported that some customers complained about the taste of the chlorine and the increased waiting time (S. Bwire & S. Stephen, personal communication, December 13, 2018).

The operator in Busime liked the GDM water kiosk with the CDB better than a GDM system without chlorination. The customers kept coming to the kiosk with dirty jerry cans despite the operator's continuous advice to the customers to clean them. Thus, the operator reflected that chlorine is required to kill the bacteria inside the water containers. Moreover, he favoured the current installation of the CDB after the clean water tank over the previous installation, where the dosage float was placed inside the clean water tank. He voiced concerns that the latter method would not chlorinate the entire tank or would drive the chlorine concentration to elevated levels at times. With the current system of having the CDB installed after the clean water tank, he encountered two problems: First, it took more time for him to operate the system since he had to leave the building to switch the main valve on or off each time people came to fetch water. Second, he lost water whenever customers stopped showing up and he had to stop the flow of water. At each stop, he lost the last 10 L of water because their chlorine concentration was higher than desired. This water was intended for the cleaning of the platform of the water kiosk. He, however, cleaned it only once in the evening and therefore did not need several buckets of water for cleaning. His solution for the two main issues, additional work and loss of sellable water, was to introduce opening hours for the water kiosk. He opened 3 times a day, each time for around 2–3 h. In his opinion, the introduction of opening hours would be accepted by the customers if he provided them with an explanation. If they did not want to wait, they left their jerry cans at the water kiosk and came back later to collect the full containers. Since most of the customers lived very close to the water kiosk, it seemed that the new opening hours did not disturb them. However, a few people complained about the taste of the chlorine and argued that there is too much chlorine in the water. The operator measured the chlorine concentration with a pooltester. Consequently, he responded to these customers that the amount of chlorine was always in the range from 0.5 to 3 mg/L. Only if the chlorine level was higher than 5 mg/L, health issues might arise (G. Ochieno, personal communication, December 12, 2018).

4.3.2 Supply Chain

Currently, the Venturi device can only be imported from MSR in Seattle. The goal is to make it available via the MSR in-market distributors throughout Africa, once the prototype is fully developed. (P. Diller, personal communication, March 12, 2019). The 1.2% chlorine solution required for the Venturi could not be acquired in Busia, Uganda, nor in Uganda's capital, Kampala, which is located around 4 h away by car from the study sites. Therefore, it was bought from a small supermarket located in Busia in Kenya.

On the other hand, all parts necessary to build the CDB can be purchased in Uganda at the time of the study. The small pipes, tubes, and connectors are sold in hardware shops in Busia in Uganda. The larger pipes, the dosage float, and the airtight bucket can be acquired in Kampala.

4.3.3 Financial Viability

According to MSR Global Health (n.d.), the Venturi should cost USD 150 when it is taken to mass-production. It has an expected lifetime of ten years. The 1.2% chlorine solution from the brand WaterGuard can be purchased for 6'1000 UGX (USD 1.60) per 500 mL bottle (K. Wanyama, personal communication, December 5, 2018). The investment costs for the CDB are USD 50 with one Henkel tablet costing 2'800 UGX (USD 0.80) (K. Wanyama, personal communication, January 28, 2018). The operational costs per m^3 of treated water amount to USD 0.82 for the Venturi and USD 0.01 for the CDB. On average around 600 m^3 of water is sold each year at each water kiosk. Table 4 reports the total costs for the treatment of 1 m^3 of water for the two chlorination devices for three different time scenarios. The time scenarios represent the time periods over which the investment costs are spread. The total costs consist of investment and operational costs.

Table 4: Total costs for different time scenarios

Scenario	Venturi [USD/m^3]	CDB [USD/m^3]
1 year	1.07	0.10
5 years	0.87	0.03
10 years	0.85	0.02

The United Nations Development Programme recommends that water costs should not exceed 3% of household income (UN, 2010). Household interviews conducted by Peter-Varbanets et al. (2017) showed that households in this study area had an average dispensable income of 78'400 UGX (USD 21.16) per month and required a monthly amount of 2.4 m^3 of water per household. On average, seven persons live in one household in this study area (Gaertner, 2019). The costs that the residents have to pay for the drinking water from the water kiosk are the investment and operational costs of the GDM filtration plus the additional costs for chlorination. According to K. Wanyama (personal communication, January 28, 2019), currently, children from the nearby school get the filtrated water for free, whereas people from the community pay a monthly fee of 3'000 UGX (USD 0.82) for three 20 L jerry cans per day or 50 UGX (USD 0.014) per jerry can in Busime. The additional costs in the ten-year scenario for chlorinating 1 m^3 of water with the Venturi and the CDB amount to USD 0.85 and USD 0.02, respectively, assuming a lifetime of 10 years for both technologies. The costs that the households pay for their monthly water purchasing in percent of their disposable income are split between filtration and chlorination in Table 5.

Table 5: Total costs in relation to household income

	Filtration	Chlorination with Venturi	Chlorination with CDB
Immediate payment	8%	10%	0.2%
Monthly payment	5%	10%	0.2%

The relative costs of filtrated water are already above the maximum value of 3% recommended by the United Nations Development Programme. If the water is chlorinated by the Venturi at the GDM water kiosk, the costs could reach up to 18% of the total available money of a household. In contrast, the additional costs of chlorinating the water with the CDB are negligible.

4.3.4 Chlorine Acceptability

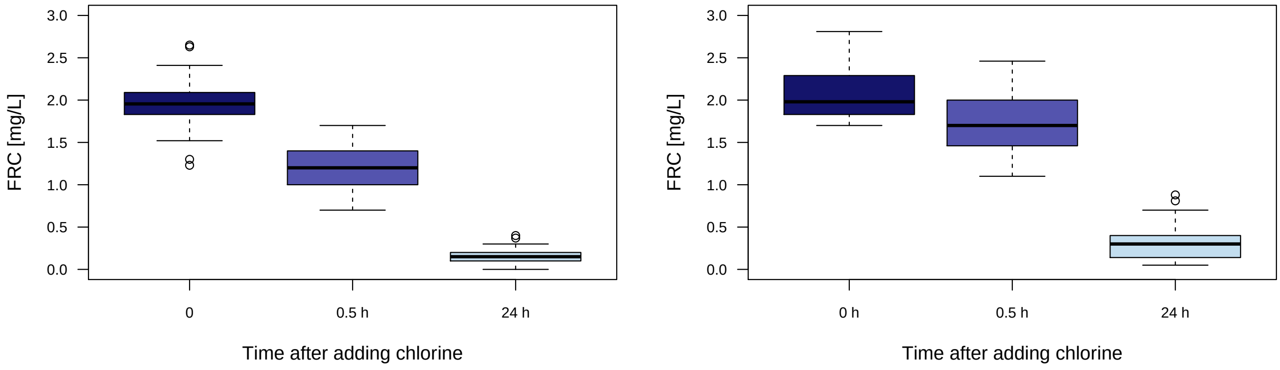
As the numbers in Table 6 demonstrate, chlorinated water is widely accepted and even the influence on taste is mostly rated positively as it directly gives an impression of increased safety. Further, almost all participants prefer the GDM water kiosks with a chlorination device over a GDM system without chlorination.

Table 6: Acceptance of chlorine by the customers

	Number of affirmative answers	N
Prefer chlorinated over unchlorinated water	89%	243
Do not like chlorinated water due to its taste	9%	
Consider chlorinated water safe to drink	96%	
Drank chlorinated water before in their life	59%	
Like the taste of the water from the Venturi	92%	42
Prefer GDM system with Venturi over no Venturi	100%	
Are bothered that only one tap is running instead of four taps	8%	
Like the taste of the water from the CDB	93%	27
Prefer GDM system with CDB over no CDB	93%	

4.4 Chlorine Decay and Water Quality

This chapter shows the chlorine decay in the water of the jerry cans during transport and storage. Figure 17a and Figure 17b illustrate that over the course of 24 h, on average, 1.8 mg/L (SD = 0.3 mg/L) of liquid chlorine and 1.8 mg/L (SD = 0.2 mg/L) of solid chlorine decays. At the water kiosk with the Venturi, the chlorine decay is higher in the first 30 min (Mean = 0.8 mg/L, SD = 0.3 mg/L) compared to the water kiosk with the CDB (Mean = 0.4 mg/L, SD = 0.2 mg/L). In the time period between 0.5 h after filling and 24 h after filling, the decrease of liquid and solid chlorine is 1 mg/L (SD = 0.2 mg/L) and 1.4 mg/L (SD = 0.3 mg/L), respectively. The mean difference in the decay of 0.34 mg/L, 95% CI [0.21, 0.47], in the time period from 0.5 h–24 h for the liquid chlorine compared to the chlorine tablet was significant, $t(65) = 4.99$, $p = .000$ (2-tailed, significance level = .05). This represents a large effect size ($r = .5$).



(a) Venturi (liquid chlorine) **(b)** CDB (solid chlorine)

Figure 17: Chlorine decay over 24 h

The number of CFU of *E. coli*/100 mL after 24 h was significantly correlated with FRC levels after 24 h of storage ($r = -.454$, $p < .001$). Figure B.2 in the Appendix plots the log-transformed CFU of *E. coli*/100 mL after 24 h versus FRC after 24 h. No *E. coli* were found in 78% of the samples (N = 106) stored for 24 h, if chlorine concentrations were $\geq$ 0.2 mg/L after 24 h. Further, 16% of those samples contained 1–10 CFU/100 mL of *E. coli* and thus, belong to water associated with low risk according to the risk categories of WHO (2017a). Moreover, 5% of those samples show an intermediate risk (11–100 CFU/100 mL of *E. coli*) and 1% a high to very high risk (> 100 CFU/100 mL of *E. coli*). Only if the chlorine concentrations were above 0.4 mg/L after 24 h, no *E. coli* were detected in the water.

4.5 Chlorine Tastings

Figure 18 illustrates the chlorine taste ratings from the three study sites. Half of the participants considered the sample with no chlorine as fair to very poor, whereas the other half rated it as fair to very good. In contrast, the taste of all chlorine samples was assessed either as very good or as good by half of the respondents. The average taste ratings for the different study sites can be found in Table B.1 in the Appendix.

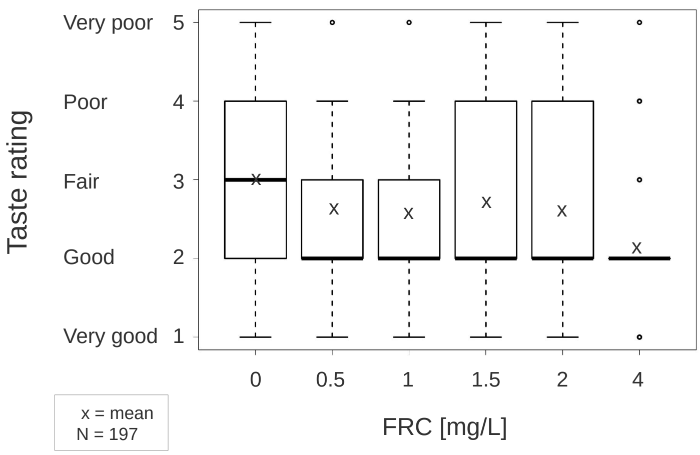


Figure 18: Chlorine taste ratings from all study sites

5 Discussion

In this chapter the obtained results are discussed. Chapters 5.1–5.4 elaborate on the extent to which the main results support the corresponding research step. Further, the findings are put in relation to the results of other studies. In Chapter 5.5 the limitations of the study are outlined.

5.1 FRC Levels in the Treated Water Provided at the Tap

The following chapters evaluate the results regarding the chlorine levels produced by the chlorination systems.

5.1.1 Venturi

Field measurements conducted over a period of one day and over a period of two weeks revealed that a stable FRC level can be achieved with the Venturi for flow rates between 6 to 20 L/min. However, when there was only a small amount of water left in the clean water tank at the end of the day, the flow rate at the tap decreased to a value below 6 L/min. At such flow rates, the venturi mechanism did not work as intended producing FRC values above 5 mg/L. Such low flow rates could last up to 1 h, a time period during which up to 15 jerry cans could be filled. According to the WHO health-based guidelines, FRC values cannot exceed 5 mg/L in drinking water if it is to be considered completely safe for lifetime consumption (WHO, 2017a). The author advised the operators to fill the chlorine tank with a reduced amount of chlorine so that all chlorine would be used up at the end of the day, when the clean water tank would be almost empty and the corresponding low flow rates would lead to high FRC values. Subsequently, each day, a few jerry cans were filled with unchlorinated water. The author of this thesis considered this to be a better option for the customers compared to the very high FRC values in the water. Nevertheless, it can also be argued that the WHO's health-based guideline value is set very conservatively. It stands to reason that the FRC concentrations would have to exceed 5 mg/L dramatically before it causes serious health damage, especially if the only alternative is drinking unchlorinated and possibly contaminated water. However, such high chlorine levels may move residents to quit purchasing water from the water kiosks and to consume less safe alternatives instead. In any case, both options regarding the high FRC values are not satisfying. The interviews with the operators also revealed that it was difficult for the operational team to follow the advice of using fewer chlorine bottles than actually required.

The Venturi is still in its prototype stage. Apart from this study, so far, it has only been tested at water kiosks in Kenya by the organisation Safe Water & Aids Project (SWAP) in partnership with Stanford University (P. Diller, personal communication, February 21, 2019). Test results from that study showed that in the course of one hour the device handles a range of flow rates from 20 to 40 L/min producing an FRC level between 1 and 1.5 mg/L, which is well within the performance of 1 mg/L that is targeted by SWAP (SWAP, 2017). Further, 86% of 144 samples taken over a period of seven months showed FRC values between 0.2 and 1.2 mg/L (Powers et al., 2019). At these water kiosks, the problem of too high FRC concentrations due to low flow rates did not occur. The reason for this is the placement of the clean water tank, which is installed on the roof of the water kiosk and thus ensured flow rates above 6 L/min. Thus, pressure head at those kiosks is higher than at the water kiosks investigated by the author (SWAP, 2017). The Venturi is designed to give a consistent FRC dose for different flow rates in the range of 5–60 L/min (SWAP, 2017; MSR Global Health, n.d.). In this study, FRC values correlated significantly with the flow rates on a measurement day where the flow rate decreased from 20–14 L/min. This observation could not be confirmed by the measurements over two weeks because the flow rate was more or less constant on these days. Therefore, to make a clear statement about the dosing dependency on the flow rates of the Venturi, FRC values have to be assessed over a longer time period for different flow rates.

5.1.2 CDB

Field measurements revealed that the CDB is not able to guarantee stable FRC concentrations because there was a high variation (0.3–3.1 mg/L) in the FRC levels over a period of four weeks. There are two main reasons for this high variation. First, at times when the solar pump did not work, and it did not rain, there was almost no water in the clean water tank. This resulted in a water level below the bent tube inside the CDB. As a result, the chlorinated water could not flow out of the bucket and, thus, the water at the tap did not get chlorinated. Second, the FRC values depend to a large extent on the flow rates. For instance, a high flow rate results in a lower hydraulic residence time in the chlorine bucket compared to a small flow rate. Thus, the contact time of the water with the chlorine tablet is shorter which leads to lower FRC values at the tap in comparison to low flow rates. From November 23 to 30 the pump did not work at its full capacity leading to a very low water level inside the clean water tank. This, in turn, caused very low flow rates. Following the repair of the solar pump on December 7, the clean water tank was again filled to capacity which led to very high flow rates. If the pump worked reliably, the amount of water in the clean water tank would not vary to such degrees and, as a direct consequence the FRC values would be much more stable.

The results from the developed model of the CDB suggest that the CDB can be improved by three different means to ensure more stable FRC levels in the treated water at the tap. First, two different slit openings at the dosage float could be applied for different flow rates. However, this strategy requires major behavioural adaptions by the operator and thus might be difficult to sustain over a longer period. Second, the volume of the chlorine bucket could be increased. A disadvantage of this approach is that a bigger bucket might be much more expensive than the existing one and a local supply chain might not be available in Uganda. Third, the flow rate to the chlorine bucket could be reduced by conducting more water through the bypass pipe. It must be investigated if this implementation affects the total flow rate. The first approach is an operational strategy whereas the last two strategies improve the design of the CDB. The improvements tackle the issue of a high variation in the hydraulic residence time for different flow rates.

It was found that the calculated rate of chlorine decay in the chlorination bucket is much higher than the one measured in the jerry cans. The ultrafiltration membrane is not very effective in the removal of dissolved organic matter and ammonia (Pi, Gao, Fan, Gong, & Wan, 2009; Gibert, Pages, Bernat, & Cortina, 2017). The concentration of total organic matter and total nitrogen in the water of the Lake Victoria amount to around 8.1 mg/L and 0.7 mg/L, respectively (Peter-Varbanets et al., 2016). This indicates that the concentrations of dissolved organic matter and ammonia in the water at the kiosk are similar or even smaller than the FRC concentrations in the bucket. Due to reactions of the dissolved components with FRC in the bucket, the concentrations of these components in the water inside the bucket might decrease to such values that only few reactions take place later in the jerry cans. This might be a reason why the observed rate of the chlorine decay in the jerry cans is much lower than the calculated one in the chlorination bucket. The reaction of chlorine with dissolved organic matter can lead to possibly toxic disinfection by-products (Zazouli & Kalankesh, 2017). Therefore, it would be important to assess in the future in addition to the microbial quality of the drinking water also the occurrence of these by-products.

5.2 Assessing the Sustainability of the Application

A sustainable implementation is possible in the case of the CDB. This device can be operated by the local community, a local supply chain is available and it is affordable and accepted by the customers. In contrast, the Venturi has to be imported from overseas and the costs cannot be supported by the local people.

Operational costs for the Venturi could, however, be reduced considerably if the liquid chlorine solution was produced locally instead of purchased from the supplier. The Mini-WATA device makes use of a simple process of electrolysis to convert salt and water into sodium hypochlorite, powered by a solar panel. The Mini-WATA technology is specifically designed for use in communities in developing countries (Antenna Foundation, 2018). A question that still needs to be addressed, however, is whether the non-stabilized chlorine solution can be used for the Venturi to achieve adequate dosing. Not only the decay of the chlorine could be an issue, but also the challenges in handling the device that may arise for the operator. Unfortunately, it was not possible to investigate these critical issues in the field because the WATA failed to work at some point, perhaps due to contact of the power cord with chlorine. This incidence reinforces the concerns regarding the feasibility of adequate handling of the WATA device by the local operational team. Huonder (2017) discovered in his study that there is a high risk of system failure with this device due to the tendency of individual parts to break down. Additionally, Huonder stated that handling and maintenance can be carried out by the operator, but only after having undergone a thorough training.

The total costs for the treatment of 1 m^3 of water for a ten-year scenario are at the higher end for the Venturi (0.85 USD/m^3) and at the lower end for the CDB (0.02 USD/m^3) compared to similar chlorination devices. Huonder (2017) demonstrated that the treatment costs of the Aquatabs Flo© are 0.27 USD/m^3 and 0.12 USD/m^3 for the dosage float placed inside the clean water tank for a ten-year scenario. The chlorination of water costs around 10 times less with the CDB, compared to placing the dosage float alone in the clean water tank. The reason is that the dosage float inside the clean water tank consumes more chlorine per treated amount of water since the tablet is in constant contact with the water.

The answers from the polls give the impression that the people in the study area were not at all disturbed by the chlorine taste of the drinking water. This could be due to the fact that the majority of the respondents had already drunk chlorinated water in their life before and is thus used to its taste. Further, participants might like the chlorine taste of the drinking water because it assures the safety of the water. However, another reason for the observed answers could be perceived social obligation. According to the answers of the interviews, longer waiting hours due to the running of one tap instead of four did only disturb a few respondents. In contrast, the operators revealed that customers do complain about longer waiting hours as well as the chlorine taste of the drinking water. Therefore, caution must be exercised in interpreting the answers from the polls.

5.3 Chlorine Decay and Water Quality

It was found that a chlorine level of 2 mg/L at the tap of the kiosk is not sufficient to guarantee a satisfying quality of drinking water at the point of consumption. This finding is based on the observation that on average 1.8 mg/L FRC decays over 24 h. The FRC level after 24 h of storage was below 0.2 mg/L in various households because the chlorine decay has a standard deviation of 0.2 mg/L for liquid and 0.3 mg/L for solid chlorine. WHO (2017a) states that the minimum FRC level at the point of consumer delivery should be at least 0.2 mg/L. Compared to Lantagne (2008), much higher rates of FRC decay over the course of 24 h were found. According to Lantagne (2008), most of the investigated samples (86.6%) with turbidity below 10 NTU, that are treated with a chlorine dose of 1.875 mg/L, boasted a minimum FRC level of 0.2 mg/L after 24 h. However, these water samples were taken from cleaned water storage containers resulting in a slower chlorine decay. In the mentioned study, most of the samples showing an FRC below 0.2 mg/L after 24 h came from jerry cans that are difficult to clean and where, for example, vegetable oil residues may have increased the chlorine demand of these samples.

The goal of the water treatment is to deliver drinking water that does not contain the faecal indicator *E. coli* (WHO, 2017a). No *E. coli* were found in 78% of the samples (N = 106) stored for 24 h if chlorine concentrations were $\geq$ 0.2 mg/L after 24 h. Only if the chlorine concentrations were above 0.4 mg/L after 24 h, no *E. coli* were detected in the water. These findings are in line with previous results. Null & Lantagne (2012) pointed out that 77% of the 589 investigated households with total chlorine residual above 0.2 mg/L after 24 h of storage manifested no *E. coli* in their ceramic pots, in contrast to only 31% of households with a total chlorine residual level below 0.2 mg/L. In another study (Meierhofer et al., 2019), it was found that water was only free of *E. coli* after 24 h of storage, if FRC levels were at least 0.4 mg/L after 24 h.

Above it was mentioned that 1.8 mg/l of FRC decayed during 24 h at both study sites. However, the chlorine decay in the first 30 min in Bulundira was double the rate observed in Busime. For both study sites, jerry cans with a similar level of cleanliness were used. This indicates that the chlorine demand of the water at the water kiosk in Bulundira was unexpectedly high. The high chlorine demand could be due to the dissolved iron observed in the water which may originate from the corrosion of some metal parts at the water kiosk, such as the sample taps. Much more solid than liquid chlorine decayed in the period from 0.5 to 24 h, showing that solid chlorine decays faster than liquid chlorine. This implies that an FRC level of 2 mg/L at the tap is not sufficient in the case of solid chlorine. In contrast, 2 mg/L might be sufficient for liquid chlorine because less than 1.8 mg/L of liquid chlorine might decay if the water has a smaller chlorine demand. Further work needs to be carried out to establish whether an FRC level of 2 mg/L at the tap is sufficient to achieve a satisfying water quality given chlorination with liquid chlorine and a chlorine demand usually observed in such water.

The microbiological water quality of the samples in this study was evaluated by testing on *E. coli* and total coliforms. Enteric viruses and protozoa are, however, more resistant to disinfection than *E. coli*. Thus, the absence of *E. coli* , while a positive signal, is not sufficient to guarantee the absence of all other organisms (WHO, 2017a). The efficiency of disinfection can be quantified with the Ct value to estimate the effect of chlorination on all three groups of pathogens. According to the Ct table provided by United States Environmental Protection Agency (1999), for water with a temperature of 25 C° and a pH of 7, as observed at the investigated water samples, a Ct value of 2 min.mg/L is required to achieve 4-log inactivation of viruses and a Ct value of 37 min.mg/L for 3-log inactivation of Giardia cysts. The resulting disinfection efficiencies of the CDB are in the range of 4 min.mg/L for the highest flow rate and 61 min.mg/L for the lowest flow rate. Since the temperature of the water is very high, these Ct values suffice to achieve 4-log inactivation of viruses. However, to obtain a 3-log inactivation of Giardia cysts for all observed flow rates, the volume of the CDB has to be increased from 30 to 250 L keeping chlorine dosage constant. In the case of the Venturi, the contact time is short because the water gets chlorinated at the moment of water collection. To achieve a Ct that ensures water free of viruses and Giardia cysts, consumers should wait 30 min before drinking the chlorinated water from the tap. Ct values above 1'000 are required for the 2-log inactivation of some other protozoan pathogens such as *Cryptosporidium* with free chlorine. Thus, the water chlorinated with the Venturi and the CDB will not be free of these microorganisms.

5.4 Chlorine Tastings

Since the participants' opinions on the taste of the water samples varied greatly, it could not be determined if the local community accepts FRC levels up to 2 mg/L in the drinking water. This study has not been able to replicate the results of previous studies that identified a chlorine threshold value at which the participants reject the water. In Ethiopia, participants did not like the taste of water at 3 mg/L chlorine, whereas in Zambia, people already considered the taste of water with 2 mg/L of chlorine as too strong and bitter (Lantagne, 2008). Crider et al. (2017) showed that the median acceptability threshold for chlorine among participants in Bangladesh was 1.25 mg/L.

Surprisingly, it seems that the respondents of this study considered the sample with no chlorine present, on average, as having the worst taste and the one with 4 mg/L chlorine as the best taste. This is primarily based on the answers supplied from participants in the chlorine tastings undertaken at the water kiosks with a chlorination device. Those respondents rated the taste of the sample without chlorine, on average, as poor. There might be various reasons for this rather unexpected result. First, bottled water, which participants were not familiar with, was used instead of the treated water from the kiosk. Bottled water was used in the tasting trial to have the same test solutions for all study sites. For instance, in Bulundira corrosion led to the formation of iron in the water resulting in a strong iron taste. Second, there is the chance that the respondents did not fully understand the meaning of the question. Possibly, they rated the perceived safety of chlorine instead of its taste. Further, social pressure could have played a role as the people knew that the chlorination device was implemented by the author of the study who conducted the tasting trial. Last, in Bulundira the chlorine tasting took place after the chlorination device was in use for several weeks. Thus, the participants might have gotten used to the taste of chlorine. To diminish the effects of social obligation and familiarity, the last chlorine tasting was undertaken at a water kiosk where no chlorination device was installed. Additionally, children were questioned who might be less influenced by social obligations compared to adults. At this tasting, the participants rated all samples as fair on average.

5.5 Limitations

A generally challenging factor was the developing context of Uganda with its very limited resources. Long distances, barely any infrastructure on the countryside, power and car breakdowns, to name only a few, complicated even simple tasks. This sometimes affected the plans of the author, requiring adaption to unforeseen problems. Further, there are specific methodological limitations to this study. Both chlorination devices were implemented in different study sites that are a 90 min car drive away from each other. It must be noted that the different contexts could have affected the device evaluations. Especially the differences in the water quality, the operators' diligence, the water flow rate and the pumps' functioning could have been impacting the device evaluations. Further, more FRC data points at different flow rates are required to quantify the variance of this data. For instance, the FRC values used to compare the empirical values to the calculated ones are point measurements which do not show the deviation of the FRC values. This could be a reason why the modeled values under- and overestimate some of the empirical values.

In addition to the colorimeter, a pooltester with a wide uncertainty range had to be used for the assessment of the chlorine decay as well as for the measurement of FRC levels at the tap conducted by the operator in Busime. Thus, the results based on measurements of the pooltester need to be interpreted with caution. The operator did some of the measurements since FRC values could not be measured regularly at both water kiosks by the author. This was mainly due to long travel times between the city and the water kiosks and between water kiosks. The daily required 3-4 driving hours were even increased at times when heavy rainfalls led to bad road conditions and hampered mobility. Another reason why the flow rate and chlorine measurements could not be conducted every day for the same period of time was the fact that the solar pumps refused to work at times. As a consequence, there was a shortage of water at the water kiosks and no data could be collected. Retrospectively, another limitation is that the valves at the CDB were not varied enough. A greater variation of the valve settings combined with a longer observation time per setting would have provided more valuable information and should thence be re-investigated.

The number of chlorine tablets required to treat 1 m^3 of water was estimated by the dissolution rate of the chlorine tablet and the flow rate required to obtain an FRC value of 2 mg/L at the taps. Thereby, the decreasing surface of the chlorine tablet was not considered in its dissolution rate calculation. Thus, there is some degree of uncertainty in the data of the operation costs of the CDB. Another limitation is imposed by the design of the chlorine tasting. The main issue is that the experiment was not randomized enough to eliminate confounding effects. On the one hand, the water samples were handed out in ascending order starting at 0 mg/L to avoid the masking effect of stronger chlorine probes over weaker ones. On the other hand, only water kiosk customers, mainly women, participated. A possible confounding effect is that the participants might have been motivated in the beginning but lost interest in the course of the experiment. Further, short time spans as in the study entail the risk of masking the taste of the next sample with the taste of the previous sample. Moreover, it was not possible to implement the chlorine tastings under standardised conditions at all study sites.

6 Conclusion

Both automatic chlorination devices could be successfully installed at the GDM water kiosks. A stable level of FRC, however, could not be provided by both of them. A sustainable implementation is only possible in the case of the CDB. The CDB is affordable, can be produced locally, and operation by the local community is possible. In contrast, the Venturi has to be imported from overseas and the costs cannot be supported by the local population. Surveys showed that the majority of the customers preferred the GDM system with a chlorination device to no chlorination. The reason given by the people was often the increased confidence in the safety of the water that was inspired by chlorination. On average 1.8 mg/L of FRC decays in the course of 24 h. Only if the chlorine concentration was above 0.4 mg/L after 24 h, no *E. coli* were detected in the water after 24 h of storage. No clear answer can be deduced from the chlorine tastings due to confounding effects such as perceived social obligations and non-randomization of the sample distribution.

Adequate chlorination at GDM systems in Uganda cannot be achieved by the Venturi for the following reasons: First, the Venturi can not guarantee stable FRC levels in the water provided at the taps due to the occurrence of high FRC concentrations at very low flow rates. Second, sustainable implementation is not ensured because the operation of the Venturi is too expensive for the local people and a local supply chain is not available. Also, the CDB does not achieve adequate chlorination at the GDM water kiosks in Uganda because no stable FRC level in the treated water at the tap could be provided over the duration of one month. Nevertheless, the CDB has some characteristics that are crucial for the study area such as the provision of a local supply chain and its affordability. Thus, mitigation strategies were developed for the CDB. The strategies include the application of two different slit openings, the reduction of the water flow to the chlorine bucket and the increase of the chlorine bucket volume. Future research should investigate if the CDB provides more stable FRC levels in the treated water at the taps by implementing these strategies. Further, it has to be examined with which strategy the CDB still meets the requirements for a sustainable implementation.

This study has gone some way towards enhancing our understanding of the effects of chlorination at water kiosks in a developing country as well as the level of chlorine necessary to achieve useful effects. Furthermore, the presented results help address the problem of finding an adequate chlorination system for GDM water kiosks in Uganda. Recontamination observed during transport and storage might be prevented with the CDB, if the hydraulic residence time variation is attenuated and a sufficient FRC level in the water at the water kiosks is provided. These findings contribute to the SDG 6.1, whose target is to guarantee "universal and equitable access to safe and affordable drinking water for all" by 2030 (UN, 2017). Safe and affordable drinking water goes along with eliminating diseases such as diarrhoea, which in turn leads to increased development and reduced poverty.

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A Appendix: Materials and Methods

A.1 Study Design

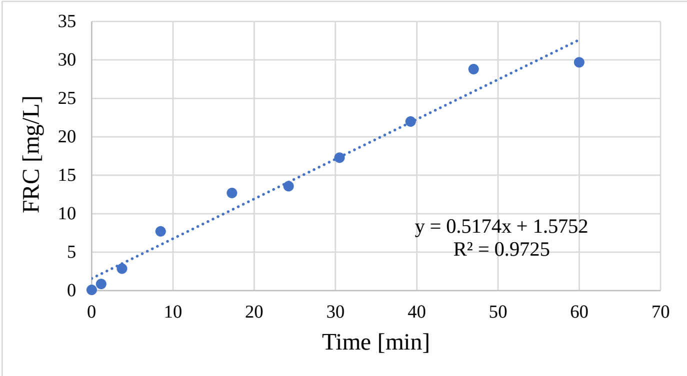

Figure A.1: Dissolution of chlorine tablet with slit opening = 30%

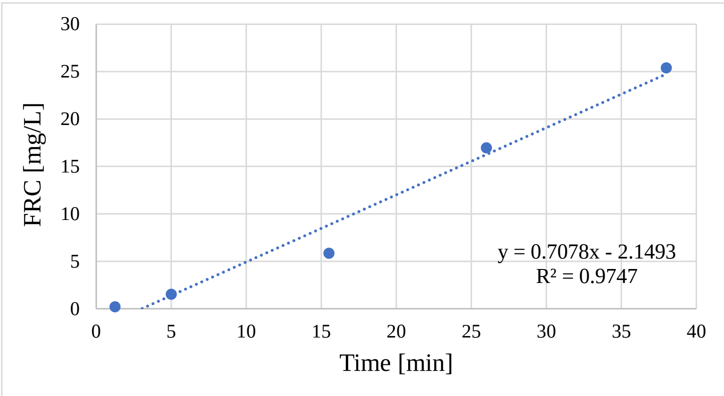

Figure A.2: Dissolution of chlorine tablet with slit opening = 50%

Table A.1: Amount of liquid chlorine mixture required for the four chlorine solutions for the chlorine tastings at the households

FRC needed incl. decay [mg/L]	FRC needed incl. decay per bottle [mg/0.5L]	**Needed amount from 1L solution [mL]**
0.7	0.35	**29**
1.2	0.6	**50**
1.7	0.85	**71**
2.2	1.1	**92**

Table A.2: Amount of liquid chlorine required for the five chlorine solutions for the chlorine tastings at the water kiosks

FRC needed incl. decay [mg/L]	FRC needed incl. decay per bucket [mg/8L]	**Needed amount from liquid chlorine [mL]**
0.7	5.6	**0.47**
1.2	9.6	**0.80**
1.7	13.6	**1.13**
2.2	17.6	**1.47**
4.2	33.6	**2.80**

A.2 Calculations

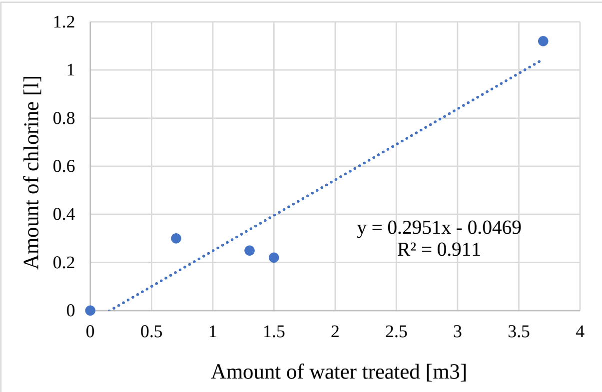

Figure A.3: Linear regression of the observed amounts of chlorine required for treating water

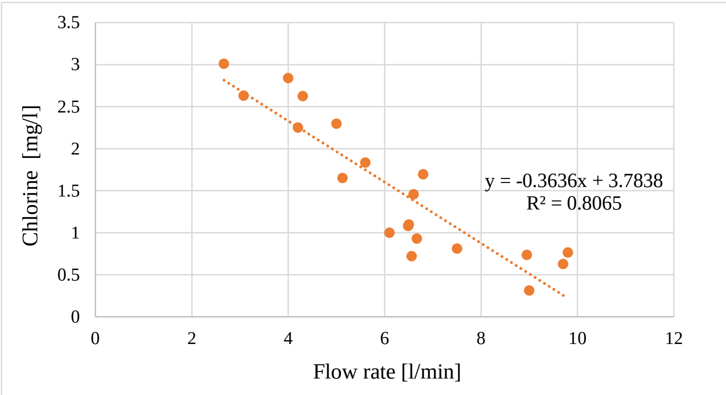

Figure A.4: Linear regression of the FRC and flow rate data points

B Appendix: Results

B.1 Theoretical Aspects

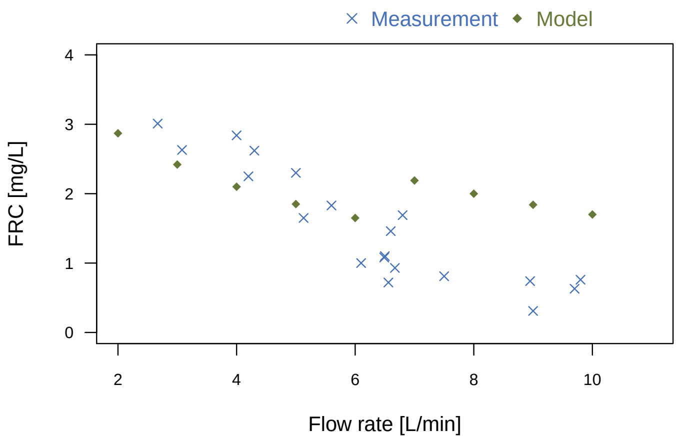

Figure B.1: Calculated vs. measured chlorine concentrations with the application of two slit openings (30% and 50%)

B.2 Chlorine Decay and Water Quality

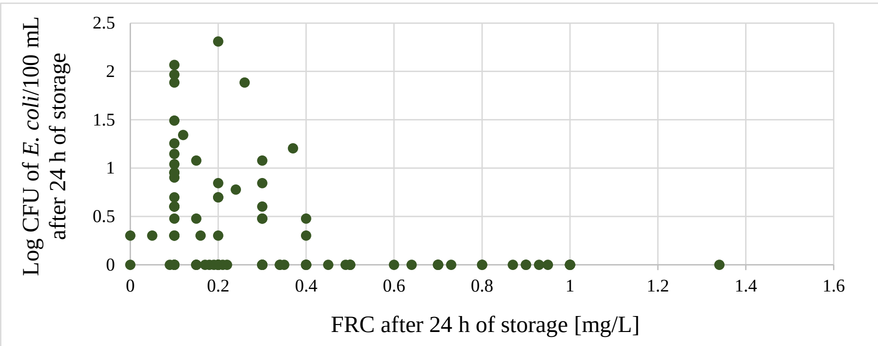

Figure B.2: Log-transformed *E. coli* vs. FRC

B.3 Chlorine Tastings

FRC [mg/L]	0	0.5	1	1.5	2	4
Households (No chlorination device)	**2.2** (0.9)	**2.5** (0.9)	**2.8** (1.0)	**2.8** (1.0)	**2.6** (1.1)	-
Kiosk 1 (With chlorination device)	**3.5** (1.1)	**2.4** (0.7)	**2.4** (0.7)	**2.6** (0.9)	**2.6** (0.9)	**1.9** (0.7)
Kiosk 2 (No chlorination device)	**2.9** (1.0)	**3.1** (1.0)	**2.7** (0.9)	**2.9** (1.0)	**2.4** (1.1)	**2.8** (1.1)
Kiosk 2 (No chlorination device) Children	**2.8** (1.0)	**2.6** (1.0)	**2.5** (0.9)	**2.6** (0.9)	**2.9** (1.0)	**2.6** (0.9)

2	**good**
3	**fair**
4	**poor**

Table B.1: Average answers (with standard deviations) from chlorine tastings