BIOSAND FILTRATION IN HOUSEHOLD DRINKING WATER TREATMENT

By

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Abstract

Household water treatment technologies provide an interim solution to drinking water provision in areas which are not yet serviced by a continuous piped connection to a communal treated source. This is a critical problem in Amerindian communities in the Guyanese hinterland region, where remote location and low population density make improving environmental health infrastructure challenging. Biosand filtration is one promising household water treatment technology available for this purpose. The overall goal of this research was to better understand, and thus improve, the biosand filter for field operation.

A field study was performed in the Amerindian community of St. Cuthbert's, Guyana. A questionnaire was implemented to determine risk factors for diarrhoeal disease, and water samples were taken from creeks and standpipes in the village and from stored drinking water in households. Serving drinking water by scooping from a bucket as opposed to pouring or using a tap or spigot was found to be a risk factor for illness, while having water piped to the household was associated with lower diarrhoeal disease rates. Post-collection water contamination was found to cause a significant decline in drinking water quality.

Adoption and sustained use of biosand filters were compared to two other prominent household water treatment methods, that being the addition of hypochlorite solution and use of a safe water storage container, and ceramic candle filtration. It was found that in St. Cuthbert's biosand filters had moderate adoption (36%) but usage was not sustained (4%). Closing interviews revealed that people found the filters too large and heavy, did not trust them, and found them too difficult to use.

The issue of the biosand filter's size and ease of use could be partially mitigated if it were possible to reduce the height of the sand column in the filter. The filter would also be easier to use if it was not necessary to add water every day.

Experiments on laboratory columns representing biosand filters determined that although the sand layer in the filters was 55 cm deep, there is little additional

benefit to each centimeter over 30 cm of filter depth, making a significant height reduction possible without compromising filter performance.

Further column experiments determined that the common field practice of extending residence periods of biosand filters from the recommended one day to two or three days did not lead to a statistically significant reduction in the filter's ability to remove *E. coli*, but did lead to anaerobic conditions within the filter and a modified nitrogen profile in filter effluent. This may impact the taste of the filtered water. In cases where influent water has high initial nitrogen content this could lead to an exceedance of World Health Organization guidelines for nitrate and nitrite in drinking water.

Although the design of biosand filters was based on the theory that a low standing head would cause intermittent operation of slow sand filters to match that of continuous operation, this research found that continuous operation of the biosand filter led to significantly improved removal of bacterial and viral indicators (3.7 $\log_{10}$ versus 1.7 $\log_{10}$ for *E. coli*, and 2.3 $\log_{10}$ versus 0.9 $\log_{10}$ for bacteriophage MS2).

Résumé

Les technologies de traitement de l'eau à domicile offrent une solution temporaire pour alimenter en eau potable les zones non encore reliées à un réseau d'apport et de traitement de l'eau communautaire. C'est un problème critique pour les communautés amérindiennes de l'arrière-pays montagneux de la Guyane, où l'isolation géographique et la faible densité démographique rendent l'amélioration des infrastructures hydriques et sanitaires difficile. Le filtre à biosable est une technologie prometteuse pour le traitement de l'eau à domicile qui serait disponible pour pallier ces contraintes. L'objectif global de cette recherche a été de mieux comprendre et d'améliorer le filtre à biosable pour son opération sur le terrain.

Une étude sur le terrain a été réalisée dans la communauté amérindienne de St Cuthbert's en Guyane. Un questionnaire a été distribué dans la communauté pour déterminer les facteurs de risques liés aux maladies diarrhéiques et des échantillons d'eau ont été prélevés des ruisseaux, des bornes-fontaines du village ainsi que des réserves d'eau entreposée dans les domiciles.

Puiser de l'eau potable directement d'un sceau avec un récipient improvisé par opposition à avoir accès à de l'eau à partir d'un robinet s'est avéré lors de l'analyse comme étant un facteur à risque pour tomber malade.

En revanche, l'accès à l'eau courante au domicile amenée par un réseau de tuyaux a été associé à des taux de maladies diarrhéiques plus faibles. La contamination de l'eau après sa collecte initiale s'est avérée comme étant un facteur causant une baisse significative de la qualité de l'eau potable.

L'adoption et l'utilisation à long terme des filtres à biosable ont été comparées à celles de deux autres technologies de traitement de l'eau à domicile très répandues: l'ajout dans l'eau d'une solution hypochlorique combiné à l'utilisation de récipients sécuritaires d'entreposage de l'eau et la filtration à base de bougies céramiques. L'étude a montré que dans St Cuthbert's les filtres à biosable ont connu un taux d'adoption modéré (36%) mais que leur utilisation n'a pas été à

long terme (4%). Des entrevues de fin d'étude ont indiqué que les habitants de la communauté ont trouvé les filtres à biosable trop larges et trop lourds, qu'ils ne leur ont pas fait confiance et, qu'ils ont trouvé leur utilisation trop difficile.

Le problème des dimensions du filtre à biosable et de sa facilité d'utilisation pourrait être partiellement atténué s'il était possible de réduire la hauteur de la colonne de sable dans le filtre. Il serait aussi plus facile d'utiliser le filtre s'il n'était pas nécessaire d'y ajouter de l'eau chaque jour.

Des essais en laboratoire sur des colonnes répliquant les filtres à biosable ont déterminé que, même si la couche de sable dans le filtre a une profondeur de 55 cm, les bénéfices pour chaque centimètre additionnel de sable au-dessus de 30 cm sont minimes. Cela permettrait une réduction significative de la hauteur du filtre sans compromettre sa performance.

D'autres essais ont déterminé que la pratique usuelle sur le terrain de prolonger le temps de résidence de l'eau dans les filtres à biosable, de la période recommandée d'un jour à deux ou trois jours, ne conduit pas à une diminution significative de la capacité du filtre à enlever les *E. coli*. Toutefois, cette pratique conduit à des conditions anaérobiques à l'intérieur du filtre et à un profil d'azote modifié dans l'effluent du filtre à cause de la nitrification. Cela pourrait avoir un impact sur le goût de l'eau filtrée. Dans les cas, où l'eau utilisée a un contenu initial d'azote élevé, les conditions anaérobiques pourraient conduire à un dépassement des recommandations de l'Organisation mondiale de la santé concernant le nitrate et le nitrite dans l'eau potable.

La conception initiale des filtres à biosable a été basée sur la théorie que le maintien d'une charge hydraulique minimale permettrait aux filtres à sable lent opérant par intermittence de performer aussi bien que ceux opérant en continue. Toutefois, cette recherche a montré que l'opération continue des filtres à biosable a permis d'améliorer significativement la diminution des indicateurs bactériens et viraux (3.7 log10 versus 1.7 log10 pour *E. coli*, et 2.3 log10 versus 0.9 log10 pour MS2 bactériophage) par rapport aux filtres à sable lent à opération intermittente.

Contribution of Authors

The manuscripts in this thesis (Chapters 3, 4, 5, and 6) will be submitted to peer-reviewed journals for publication. Candice Young-Rojanschi designed the experiments, performed the field and laboratory work, analyzed the data, and prepared the manuscripts. Dr. Chandra Madramootoo was the research supervisor and provided guidance at all stages of the experimental design and analysis, as well as editing and review of the manuscripts. Savitri Jettoo is listed as third author of Chapter 3. Her contribution included feedback and support on the experimental design, logistical support of the work, and editorial assistance in the manuscript preparation.

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List of Symbols and Abbreviations

BSF	Biosand filter
CARIWIN	Caribbean Water Initiative
cfu	Colony forming units
DO	Dissolved oxygen
EBCT	Empty bed contact time
EC	Electrical conductivity
E. coli	Escherichia coli
GPS	Global positioning system
GWI	Guyana Water Incorporated
HWTS	Household water treatment and safe storage
Hydromet	Hydrometeorological Service of Guyana
IOSSF	Intermittently operated slow sand filter
LR	Likelihood ratio
N	Nitrogen
NTU	Nephelometric Turbidity Units
PCA	Principal component analysis
pfu	Plaque forming units
ROC	Receiver operating curve
SSF	Slow sand filter
TDS	Total dissolved solids

TTC	Thermotolerant coliform colonies
UNICEF	United Nations Children's Fund
UV	Ultraviolet
WASH	Water, sanitation, and hygiene
WHO	World Health Organization

CHAPTER 1 Research Problem and Objectives

1.1 Research Problem

Inadequate sanitation, personal and domestic hygiene, water quantity, and drinking water quality are estimated to be responsible for 88% (Black et al., 2003) of the approximately 1.9 million deaths a year in the world attributable to diarrhoeal disease (WHO 2009). The majority of these deaths are of children under 5, for whom diarrhoeal disease accounts for 17% of mortality (Mathers et al., 2009; WHO, 2009).

Extending access to safe drinking water has proven difficult in many countries. Challenges to achieving this goal include the remote location of some settlements, low population density, lack of treatment plant operator training, and inadequate funding for the operation of treatment and distribution systems. An additional issue receiving increased attention over the last decade is that of post-collection contamination of drinking water through distribution or transport, and storage. The concept of household water treatment and safe storage (HWTS), also known as point-of-use treatment and storage, has emerged within the field of environmental health engineering in response to these issues.

However, research is lacking as to how sustainable and effective HWTS is in field settings (Schmidt and Cairncross, 2009a). As there are few completed studies, the standard practice is to group technologies under the heading "HWTS" (Clasen et al., 2007; Fewtrell et al., 2005; Waddington et al., 2009) despite differences in sustainability and effectiveness (Hunter, 2009). When technologies are compared, conclusions are drawn based on studies from different countries and continents over different time frames. Few studies have compared technologies within the same community using the same water source over the same time period.

There are still large knowledge gaps for all HWTS technologies, especially in terms of uptake and long-term usage, and there is some suggestion that long-term continuity rates are much lower than the published short-term efficacy studies would suggest (Arnold et al., 2009; Luby et al., 2008).

Along with ceramic filters, biosand filters (BSF) are among the most promising of the HWTS technologies (Hunter, 2009; Sobsey et al., 2008). As of mid-2009, it was estimated that more than 200,000 BSF were in operation in 70 countries (CAWST, 2009).

However, research on BSF is inadequate (Hunter, 2009). Even within controlled laboratory settings, BSF do not meet the same level of indicator microorganism removal as conventional slow sand filters (Sobsey et al., 2008; Stauber et al., 2009). Laboratory trials have been promising for the removal of protozoan (Palmateer et al., 1999), bacterial (Buzanis, 1995; Elliott et al., 2008; Palmateer et al., 1999), and viral (Elliott et al., 2011) indicator species, but the results of field trials have been mixed. Studies have found that filters do not achieve the same level of performance at removing indicator organisms as observed in the laboratory (Baumgartner et al., 2007; Earwaker, 2006; Stauber et al., 2009), with some studies finding insignificant removals or actual water quality degradation with some influent waters (Chiew et al., 2009; Jenkins et al., 2009).

Further research is necessary to determine whether HWTS is sustainable in target populations, and which factors are more likely to promote adoption and sustained usage. Research is also necessary to understand the processes involved in BSF and what factors influence performance.

1.2 Objectives

The overarching goal of this study was to improve the performance of BSF in field settings through understanding the constraints of HWTS in a community, distinguishing the effects of intermittent versus continuous operation of BSF, and identifying the impact of residence time on filter performance.

1.2.1 Specific Objectives

The specific objectives of this study were to:

i. Compare the performance and sustainability of BSF with other HWTS methods, namely ceramic candle filters and hypochlorite solution, in the village of St. Cuthbert's, Guyana.
ii. Evaluate the impact of intermittent versus continuous operation on BSF performance.
iii. Evaluate the impact of multi-day residence periods on BSF performance.

1.3 Organization of thesis

This thesis is presented in manuscript format.

The second chapter of the thesis is a general literature review of the field of household water treatment and of BSF in particular. Like the structure of the literature review, the structure of the manuscript portion of this thesis (Chap. 3-6), is organized to start broadly and become more specific with regards to BSF.

Chapter 3 presents the results of a field study in the village of St. Cuthbert's, Guyana starting with a baseline description of water, sanitation, and hygiene in the community, including source and household water quality. Chapter 4 presents the results of the application of three different HWTS technologies in this village.

Chapter 5 investigates BSF performance in the laboratory, looking at variability between filters, hydraulic operation, and how it compares to conventional slow sand filtration (SSF). Chapter 6 looks specifically at how lengthened residence periods, as noted in St Cuthbert's, impact filter performance.

The thesis presents general conclusions and recommendations for further research in chapter 7, and lists the major contributions to knowledge in chapter 8.

1.4 Scope and Limitations

The field portion of this study was performed within a single village, St. Cuthbert's, Guyana, at a particular point in time, 2008-2010. Though the observations from this village are helpful in understanding the general context of household water in an Amerindian community in Guyana, the results from this community are not directly transferable to other communities or other points in time.

The field study included only three HWTS methods: BSF, ceramic candle filters, and liquid chlorine addition to a safe water vessel. These three are among the most promising methods available at present. Limitations in acquiring materials and strong negative response amongst community members during initial discussions excluded other prominent methods, such as ceramic pot filters, solar disinfection (SODIS), and PUR (coagulation plus chlorination sachets). The trials were not blinded.

Many factors influence HWTS performance and acceptance. This research is limited to investigating hydraulic operational design parameters within the limits observed in practice and as described by the existing literature. Other parameters, such as water hardness, metals, alkalinity, and pH may also play a role in filter performance but they are beyond the scope of this study.

The water quality indicator in the field portion of this study is thermotolerant coliform colony forming units (cfu) per 100mL. These are an imperfect indicator in tropical climates, as they may be non-faecal in origin and have been found in some cases to multiply in environmental waters (Gleeson and Gray, 1997). However, this remains the standard indicator in accordance with the World Health Organization (WHO) water quality guidelines (WHO, 2008).

Escherichia coli B was used as the bacterial indicator in the laboratory study. This is a standard indicator organism in the field of water treatment and saturated porous media studies, though other indicators may behave differently.

CHAPTER 2 Literature Review

2.1 Water, sanitation, hygiene, and health

In 1854, epidemiologist Dr. John Snow closed London's Broad Street pump and demonstrated that the spread of a cholera epidemic was due not to contaminated air, or "miasma", but rather to contaminated water. This was followed shortly afterwards by discoveries regarding waterborne transmission of typhoid and amoebic dysentery, and Louis Pasteur's 1864 statement of germ theory (Crittenden et al., 2005). These triggered a series of intensive water supply and excreta disposal improvements in Europe and North America over the period of 1860 to 1920, resulting in a decline of deaths due to typhoid, cholera, and diarrhoeal disease (Esrey et al., 1985).

All "waterborne" infections may also be transmitted through any other fecal-oral transmission route (Cairncross and Feachem, 2003). The primary fecal-oral transmission routes are summarized in the classic F-diagram, shown below (Figure 2-1). Typical environmental health engineering interventions used to reduce the transmission of fecal-oral infections fall into four categories: sanitation (excreta disposal), water quantity, hygiene, and water quality (Jensen et al., 2004).

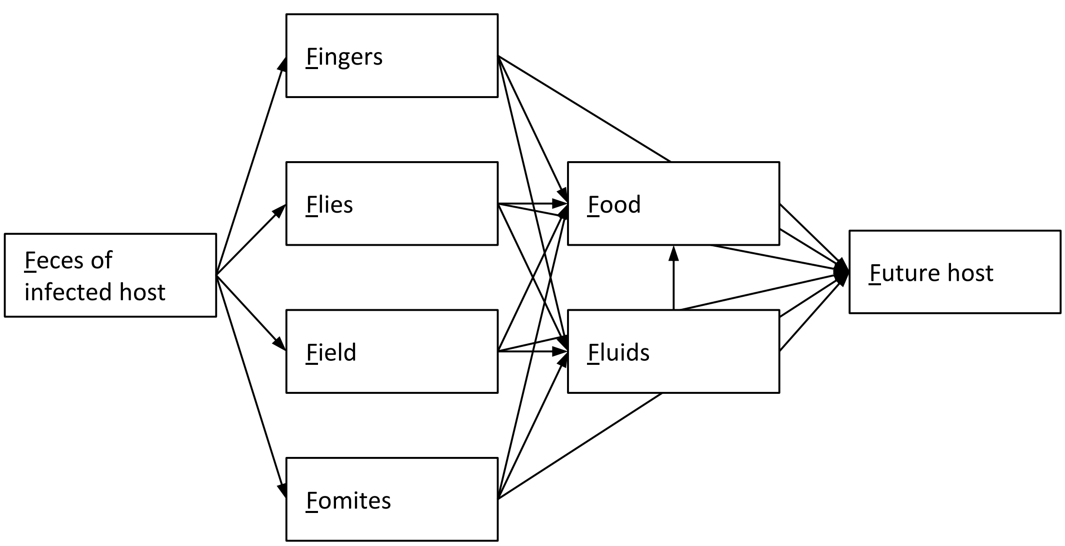

Figure 2-1 F diagram modified from Curtis et al. (2000) & Wagner and Lanoix (1958)

There is some uncertainty regarding the significance of each transmission path. Deconstructing transmission routes to determine how particular individuals were infected is difficult, as the infected host themselves may be asymptomatic and unaware that they are infectious (Eisenberg et al., 2007), and some infections do not result in immediate symptoms, but rather have extended incubation periods. Giardiasis, for example, can have an incubation period of several weeks, making it difficult to pinpoint the source of exposure (Karon et al., 2011). Briscoe (1984) argued that in many communities in the developing world, citizens are exposed to so many pathogens that even if the primary transmission route is eliminated, residual pathways may be sufficient to maintain similar rates of diarrhoeal disease unless also mitigated.

By the 1980's, the dominant paradigm regarding diarrhoeal disease prevention was that providing sanitation facilities and an adequate quantity of water to a community was more important than the quality of the water that was supplied (Murcott, 2006). This was supported by two influential review papers summarizing published studies on the success of various interventions in the reduction of water related illnesses (Esrey et al., 1985; Esrey et al., 1991).

Despite the early successes in Europe and North America, diarrhoeal disease rates remained high in the rest of the world. In 1980 it was estimated that 4.6 million children were dying each year due to diarrhoeal diseases (Snyder and Merson, 1982). In a global push to reduce child mortality and morbidity due to diarrhoea, the 1980's were declared the International Drinking Water Supply and Sanitation Decade by the World Health Organization (WHO). It was expected that, as had occurred earlier in Europe and North America, the construction of water supply and sanitation infrastructure would significantly decrease diarrhoeal disease mortality and morbidity (Esrey et al., 1985).

However, although mortality did decline, primarily due to extending the availability of medical care and the use of oral rehydration therapy, morbidity did not (Kosek et al., 2003).

There is some disagreement as to why the expected decrease did not occur. Kosek et al. (2003) cautioned that the definition of diarrhoea differed between studies, and that study methodologies have changed over time, making comparison difficult. Bartram and Cairncross (2010) argue that the increase in water and sanitation infrastructure coverage did not actually occur as rapidly or as effectively as is sometimes claimed. They also point out that the complex interactions between diarrhoea and other major causes of mortality and morbidity such as malnutrition, pneumonia, and tuberculosis, and the differences between geographical regions, make interpretation of the data very challenging. Others, however, took this as a reason to question the dominant paradigm that water quantity was more important than water quality (Clasen and Cairncross, 2004).

2.1.1 Household water treatment

In the late 1990s and at the start of the 21st century, some researchers critiqued Esrey et al.'s earlier reviews for only including interventions regarding water quality improvements at the source (Murcott, 2006). The benefits of treatment systems are reduced when operation and maintenance of the system fails. Challenges exist with maintaining and operating treatment plants in communities which have received their system as an external intervention. There may be an unclear distribution of responsibility, lack of a sense of ownership, confusion over payment, and lack of training leading to maintenance eventually being neglected and the system running down (Zwane and Kremer, 2007).

In addition, providing an inadequate water quantity, or providing water that is "safe" but unpleasant to drink due to colour, odour, taste, etc., may lead to people supplementing their water with unsafe sources (Huisman and Wood, 1974; Hunter et al., 2009). Even in the case where water is provided pathogen-free to the public, such as from a treatment plant or borehole, problems exist when it is re-contaminated during transport and storage, as occurs with intermittent piped service, communal taps, or trucked service (Clasen and Bastable, 2003; Sobsey, 2002; Wright et al., 2004)

There is no consensus on the importance of post-collection water contamination. VanDerslice and Briscoe (1993) suggested that because family members are likely to develop an immunity to pathogens commonly present within their household, or infect one another more efficiently through other exposure routes, in-house water contamination may not significantly increase a person's risk of diarrhoeal disease. Whereas domestic contamination originates from a family member's own feces, source water contamination originates from other people's feces and may include pathogens that the family has not yet been exposed to (Cairncross et al., 1996; Vanderslice and Briscoe, 1993). However, the group most at risk for diarrhoeal disease is the very young, especially weaning children, who would not yet have developed immunity to familial pathogens, a process which requires time. As such, others argue that the domestic domain remains important for the transmission of diarrhoeal disease, especially as it relates to morbidity and mortality in children under 5 years old (Gundry et al., 2004).

Fewtrell et al. (2005) performed a meta-analysis of environmental engineering methods of reducing diarrhoeal disease, this time including water treatment within the household as a separate category. They found it to be one of the most effective ways of reducing diarrhoea, with an average disease reduction of 33% (Fewtrell et al., 2005). Household water treatment and safe storage (HWTS) was found to be effective even in cases where the initial source water was of high quality (Clasen et al., 2007). The simplest and most common form is boiling, used by an estimated 21% of households in low and middle-income countries (as defined by the World Bank) for which data are available (Rosa and Clasen, 2010).

While the WHO and a body of researchers advocate the scaling up of HWTS as an intermediate step for use in areas where low population density, remoteness, or other factors (logistical, political, cost-related, etc.) prevent the introduction of an effective and sustainable centralized treatment system with distribution to each household (Clasen, 2009; Clasen et al., 2007), there is also a significant opposition who argue that there is not enough evidence at this time to justify preferring HWTS to other interventions There has been criticism that studies on

HWTS have been done with small populations on short time scales, while longer-term studies show smaller impacts, that some researchers have undeclared conflicts of interest when testing products, that there is evidence of publication bias in the literature, and that there is no evidence that HWTS interventions are sustainable (Schmidt and Cairncross, 2009a, b; Waddington et al., 2009).

In contrast, while acknowledging the concerns presented earlier in that same year, in the discussion of his meta-analysis, Hunter (2009) goes as far as stating that, "… the clear effectiveness of the ceramic filter in this analysis would make further controlled trials unethical. Research should focus primarily on how to increase uptake and sustainability of the intervention."

The decade ended with conflicting estimates of effect. By rejecting studies they found questionable, Cairncross et al.'s meta-analysis estimated only 17% disease reduction due to water quality improvements, compared to 36% due to improved sanitation (Cairncross et al., 2010). Others have chosen to accept and use Fewtrell et al.'s 2005 results of 33% disease reduction (Fabiszewski de Aceituno et al., 2012).

2.1.2 Common HWTS Methods

There are five main HWTS technologies which have demonstrated microbial removal efficacy and disease reduction in trials: chlorination with safe storage, combined chlorination-coagulation systems, solar disinfection (SODIS), ceramic filtration, and biosand filtration (Sobsey et al., 2008). However, Hunter's (2009) meta-analysis found little or no health benefit of the first three of these HWTS technologies 12 months after their introduction. This may have been due to households stopping use of the treatment over time, or to the scarcity of studies available which look at long term effects. Ceramic filters were found to have sustained positive health impacts in the meta-analysis. Biosand filters were not able to be analyzed due to a lack of studies.

Chlorination

With chlorination, users mix a small, measured amount of concentrated chlorine with a given volume of the water to be treated in a safe water storage container. A safe storage container is defined as one whose opening is too small to allow the introduction of a hand. After 30 minutes of contact time the water is available for use and is served either by pouring or with a tap or spigot.

Chlorine is very effective against a range of microorganisms, with removal rates of 3 $\log_{10}$ in field studies for indicator viruses, bacteria, and protozoa (Sobsey et al., 2008).

Liquid hypochlorite solution is generally an inexpensive product, with chlorine tablets being somewhat more expensive. As the chlorine is a consumable product and must be continuously repurchased, a dependable supply chain must be available.

High levels of organic carbon in the source water may result in the formation of carcinogenic disinfection by-products, namely trihalomethanes (THM). However, studies by Lantagne et al. found that the low dose used in HWTS applications was not sufficient to develop THMs to a level exceeding WHO health guidelines for the range of source waters they tested (Lantagne et al., 2008; Lantagne et al., 2010).

The effectiveness of chlorination can be reduced by turbidity and chlorine is only minimally effective against *Cryptosporidium parvum* oocysts (Sobsey et al., 2008).

Coagulation/chlorination

Several commercial technologies are available which combine a chemical coagulant-flocculent with chlorine in a dry granular form, usually sold in pre-measured sachets. Users add a sachet of the product to a given volume of water, vigorously mix, allow for the instructed contact time (usually approximately 30 minutes), then decant the supernatant and filter through a cloth. A sludge layer is left behind that must be properly disposed of. Like chlorine, the product is a consumable, and a reliable supply chain is necessary for its use.

These products are more expensive than chlorine alone and require more effort, but are capable of treating more challenging waters, such as those with high levels of turbidity. Field effectiveness is 7 $\log_{10}$ removal of bacteria, 2.5 to 4 $\log_{10}$ removal of viruses, and 3 $\log_{10}$ removal of protozoa (Sobsey et al., 2008).

SODIS

SODIS depends on solar radiation to treat water. Transparent polyethylene terephthalate (PET or PETE) bottles are filled with aerated source water and placed in the sun. The treatment mechanisms are ultraviolet radiation and heat. Aeration occurs by shaking the bottle well after first filling it with the water to be treated. SODIS is a very inexpensive technology, as it is possible to use discarded soft drink bottles as treatment containers. There is little risk of recontamination, as the treatment bottles also act as the treated water storage bottles. SODIS is less effective with waters which are turbid. Many bottles are necessary, and the bottles stop working once they become scuffed.

Field effectiveness is 3 $\log_{10}$ removal of bacteria, 2 $\log_{10}$ removal of viruses, and 1 $\log_{10}$ removal of protozoa. This is lower than laboratory trials have achieved. Effectiveness is impacted by the intensity of sunlight, temperature, water oxygenation, and the bottle diameter (Sobsey et al., 2008).

Some users object to the taste of SODIS-treated water as it tends to take on a distinct flavour from the plastic bottle. The water is also warmed in the process, which some users may object to.

Ceramic filtration

Ceramic filters are composed of an influent and effluent reservoir, with a porous ceramic barrier between through which water must percolate. Water is accessed from the effluent reservoir using a tap or spigot. The ceramic barrier is often coated with colloidal silver as an additional treatment step. There are two main forms of ceramic barrier. One is pot shaped, forming the base of the influent reservoir and top of the effluent reservoir. The other is candle shaped, with the ceramic elements installed by drilling through the base of the influent reservoir. Water filters through the ceramic candle into its hollow centre, and drains via a small pipe to the effluent reservoir. The candle elements are often filled with activated carbon as an additional treatment mechanism and to improve taste.

Sobsey et al. (2008) listed field effectiveness of ceramic filtration at 2 $\log_{10}$ removal of bacteria, 0.5 $\log_{10}$ removal of viruses, and 4 $\log_{10}$ removal of protozoa.

Although one of the few HWTS technologies with proven sustained effectiveness (Hunter, 2009), the ceramic elements are quite fragile, and long-term use is limited by breakage (Brown et al., 2009).

2.2 Biosand Filters

Sobsey et al. (2008) highlight biosand filters as one of the most promising HWTS technologies. Biosand filters (BSF), are biologically-active granular media filters that were developed in the early 1990s based on conventional slow sand filtration (SSF).

2.2.1 Conventional slow sand filtration

History of slow sand filtration

SSF has been used to treat water for over two centuries. The first recorded slow sand filter was developed in 1804 by John Gibb in Paisley, Scotland. Gibb treated the water for his bleachery and then sold the excess treated water to the public. After 25 years of modifications and improvements, both by Gibb and others, the first slow sand filter for public drinking water supply was designed in 1829 by James Simpson for the Chelsea Water Works Company in London. In 1852 the Metropolis Water Act was passed, requiring all water extracted for public consumption from the Thames River within five miles of St. Paul's Cathedral to be filtered (Huisman and Wood, 1974). The basic process of SSF has changed little since the 1829 model (Crittenden et al., 2005).

The technology quickly spread throughout Europe (Hendricks, 1991) but didn't arrive in North America until 1874, when it was applied in Poughkeepsie, New York (Crittenden et al., 2005).

In 1892, the value of these filters was dramatically illustrated when a cholera epidemic struck Hamburg, Germany while sparing the neighbouring city of Altona, despite the location of Altona's drinking water intake being downstream of Hamburg's infected sewage discharge. Altona's drinking water was treated with SSF. A similar demonstration occurred in Lawrence, Massachusetts when typhoid cases decreased dramatically after SSFs were installed (Crittenden et al., 2005).

The conventional treatment train of rapid sand filtration combined with coagulation and chlorination was developed in the 1880's. Rapid sand filters can accommodate loading rates up to 100 times greater than SSF, and thus require a significantly smaller plant footprint. By the mid-twentieth century, rapid sand filtration was the dominant treatment technology and SSF was rare. In the 1980's, only 50 of 50 000 municipal treatment systems in the U.S. used SSF (Crittenden et al., 2005).

Interest in SSF was renewed in the 1980's for small community water supplies due to its cost effectiveness, simplicity of operation, and effectiveness at removing *Cryptosporidium* (Crittenden et al., 2005). Parts of London, England, and Amsterdam, Netherlands, still use SSF as part of their treatment systems (Broder and Byron, 2005).

Components

There are three components of the SSF which are important for treatment; the supernatant, the schmutzdecke, and the media bed (Figure 2-2).

Supernatant

The supernatant, or the water layer above the sand surface, provides a pressure head to overcome filter head loss and allow flow through the media bed. It also provides a waiting period of several hours before filtration to allow for sedimentation of larger particles onto the sand surface, particle agglomeration, and oxidation. (Hendricks, 1991).

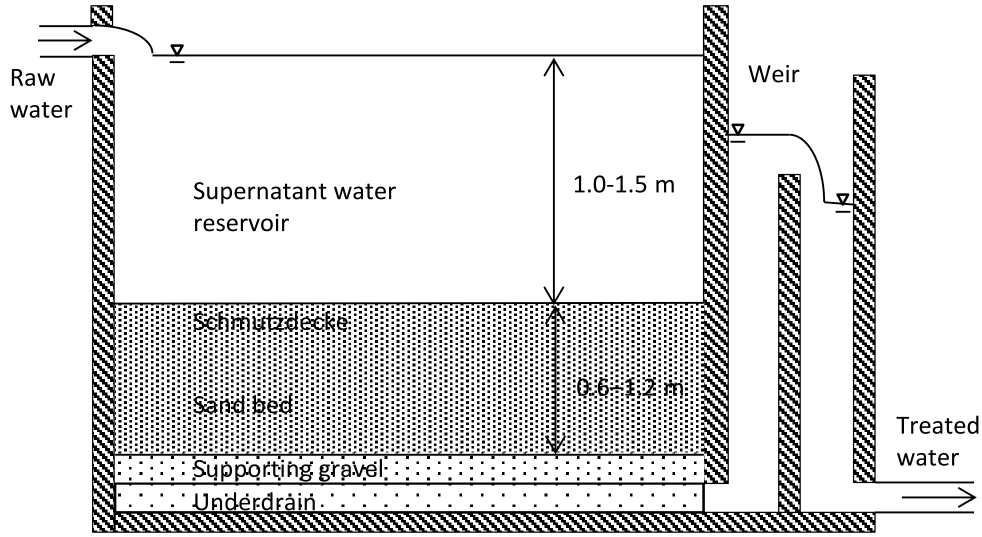

Figure 2-2 Elements of a slow sand filter (adapted from Huisman and Wood (1974))

Schmutzdecke

The schmutzdecke (from German, meaning "dirt cover") of a slow sand filter consists of both the filter cake or slime layer above the sand composed of inert and biological material (Jellison et al., 2000), and the biologically active region in the sand bed immediately below. There is no significant difference in bacterial removal by the filter cake or the immediately underlying biologically active layer (Ungar and Collins, 2008). The term is not used consistently in the literature, however, and some researchers and practitioners use the term to refer only to the filter cake (Weber-Shirk and Dick, 1997), or only to visible biofilms (Palmateer et al., 1999).

The biologically active region is not clearly delineated within the filter, as some biological activity occurs throughout the entire filter bed. However, the bulk of biological activity occurs within the schmutzdecke, leading to bioclogging (Mauclaire et al., 2006) and disproportionate head loss by depth in this region as compared to the rest of the filter bed (Petry-Hansen et al., 2006; Ungar and Collins, 2008). Ungar and Collins (2008) estimate the thickness of a typical schmutzdecke at 7.5 minutes of empty bed contact time (EBCT), where EBCT is the ratio between bed depth and hydraulic loading rate. This leads to a schmutzdecke thickness of about 1 to 2 cm in a typical filter, which they estimate has a hydraulic loading rate of 0.13 m/h to 0.25 m/h.

The schmutzdecke is credited with the majority of *E. coli* removal in SSF, with studies indicating 1-2 log greater removal of *E. coli* in filters with a schmutzdecke than filters without (Bellamy et al., 1985; Hijnen et al., 2004).

Also significant in Ungar and Collins' (2008) research was the issue of filter ripening (the period during which a filter develops a schmutzdecke) and recovery after schmutzdecke removal, as occurs during filter maintenance. They found that *E. coli* removal was not significantly related to biomass developed in the schmutzdecke, as measured by gross phospholipids, carbohydrates, and proteins. Nor was schmutzdecke development or ripening significantly related to biomass already accumulated in the media. In experiments on filter ripening in which microbial activity was inhibited with Sodium azide, biological mechanisms were found to be significant, with non-inhibited filters performing significantly better than inhibited filters. However, inhibited filters still exhibited some ripening behaviour with improved *E. coli* removal over time (Weber-Shirk and Dick, 1997). In an earlier study, 60.1% of total coliforms were removed in several test filters where biological activity was suppressed (Bellamy et al., 1985) suggesting the presence of physico-chemical mechanisms in addition to biological activity as a removal mechanism (Weber-Shirk and Chan, 2007).

Media Bed

The 0.3 to 0.4 m of media under the schmutzdecke houses microorganisms involved in the "purifying" process. Below that, a further 0.4 to 0.5 m of media is thought to accommodate mineral oxidization chemical reactions. It is recommended that the granular filter media be hard and durable, with no clay, loam or biodegradable organic matter composing the media itself. The media is most usually sand, though crushed coral and even rice husks have been used successfully. Additional layers of 0.1 m depth of activated carbon, for waters which have high taste and odour causing compounds, or crushed shells, for aggressive or corrosive waters, are sometimes incorporated into the bottom of the media bed (Huisman and Wood, 1974).

Although the schmutzdecke removes an order of magnitude more bacteria than the rest of the filter bed, the rest of the filter bed still significantly contributes to microorganism removal (Ungar and Collins, 2008). Virus removal, for example, occurs not within the schmutzdecke, but rather within the media bed (Hijnen et al., 2004).

Intermittent operation of SSF

Intermittent, or "start-stop", operation of conventional slow sand filters has been shown to be detrimental to effluent quality, and has been strongly discouraged in the literature (Huisman and Wood, 1974; Logsdon et al., 2002; Niquette et al., 1998; Paramasivam et al., 1980; Petry-Hansen et al., 2006).

Paramasivam et al. (1980) noted that many small communities in India were not operating their slow sand filters continuously due to a lack of resources and trained treatment plant operators. They studied the impact of what they identified as a typical intermittent operation schedule, in which filters were operated for eight hours each day, then paused overnight. They used three pilot scale filters. Effluent grab samples from the filters showed that water corresponding to that which had sat deep within the filter bed during the paused period had a quality similar to that from a continuous run, with *E. coli* counts below the experimental detection limit and recorded as zero. However, water corresponding to that which would have been in the schmutzdecke during the paused period had higher bacterial counts, sometimes exceeding that of the raw water, and low DO. In most cases the filters recovered after some hours and by the end of the daily run performed similarly to those which had run continuously (Paramasivam et al., 1980).

A study undertaken in Laval, Quebec, on a biologically-active carbon filter showed a decline in effluent DO from 10 mg/L to 2 mg/L after a 24 hour lag period. This lead to anoxic conditions within the bed and the production of ammonia from decaying organic matter (Niquette et al., 1998).

2.2.2 Development of BSF

A key advantage to intermittent operation is that it allows the filters to be scaled down to be used at a household scale without the need for pumping (Buzanis, 1995; Sobsey et al., 2008) (Figure 2-3).

One theory of why poor results were noted from the intermittent operation of conventional SSF is that anoxic conditions developed within the filter's schmutzdecke (Buzanis, 1995). When operated intermittently, the SSF retained a constant supernatant depth above the schmutzdecke of 1.0 to 1.5 m.

The design of the biosand filter was based on the hypothesis that reducing the standing head within the filter during the idle period would maintain aerobic conditions within the schmutzdecke and thus overcome the problems conventional SSF faced in intermittent operation (Buzanis, 1995).

A small-scale filter was designed and tested with the modification of a lowered filter outlet to leave a minimum supernatant depth, or standing head, of only 50 mm above the sand surface during periods of no flow (Figure 2-4). The 50 mm standing head was designed to be shallow enough to allow for the diffusion of dissolved oxygen to the schmutzdecke to maintain aerobic conditions, yet also ensure continued media saturation. In contrast, the recommended minimum supernatant depth for a SFF is 0.30 m, in order to avoid scouring of the sand surface by influent water (Hendricks, 1991), and the usual depth is in the range of 1.0 to 1.5 m (Huisman and Wood, 1974). Scouring was mitigated in the new filter by the addition of a diffuser plate.

Figure 2-3 Photo of BSF

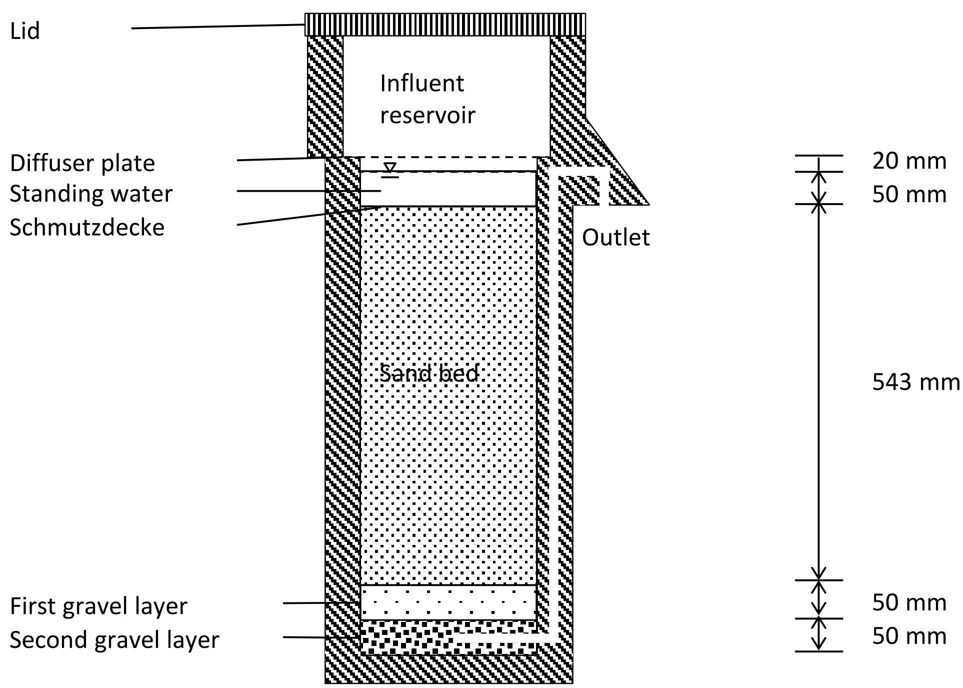

Figure 2-4 Schematic of BSF. Modified from CAWST (2012)

Unlike the intermittent operation of conventional SSF as studied by Paramasivam et al. (1980), the BSF operates by applying the full quantity of influent water at one time. This displaces the existing pore water in the filter, which is then discharged from the outlet tube. The water which has just been added remains in the filter until the next application. The time between applications is referred to as the residence period.

Over the 60-day period of his initial study, Buzanis (1995) took effluent grab samples from his test filter after 1, 5, 10, 15, and 20 L of water had been filtered. In order to describe DO consumption in the filters, he calculated to which media depth the sample corresponded: the 1 L sample corresponded to the filter underdrain, the 5 L sample to the media bed, the 10 L sample to the schmutzdecke, while the 15 and 20 L samples corresponded to water which had not remained in the filter during the residence period. Similar to the results of Paramasivam et al. (1980), the lowest DO concentrations corresponded to water which had remained in the schmutzdecke. The DO in the water which had remained deeper in the media bed was only slightly lower than that of the water which had not remained in the filter during the residence period, which, in turn, was not much lower than that of the influent water. He concluded that little oxygen was consumed during filtration, with the majority of oxygen consumption during the residence period occurring within the schmutzdecke (Buzanis, 1995).

Because all effluent grab samples were oxygen-rich, Buzanis concluded that anaerobic conditions do not occur in BSFs (Buzanis, 1995). However, he did not account for possible aeration at the filter outlet during sample collection. Nonetheless, in the absence of further studies, this work remains the reference for DO in the BSF media profile (Elliott et al., 2011).

Early BSF laboratory trials resulted in 1.4 $\log_{10}$ removal of fecal coliforms. The filter then underwent successful field trials in Nicaragua and Honduras (Buzanis, 1995). The BSF was patented for commercial purposes, but the patent was left open for humanitarian applications.

2.2.3 Differences between SSF and BSF

In the literature, the BSF is often described simply as a small scale SSF which is operated intermittently (Ghebremichael et al., 2012; Kubare and Haarhoff, 2010), or as a slightly modified version of the conventional slow sand filter (Chiew et al., 2009). However, in addition to continuous versus intermittent operation, several structural and operational differences exist between SSF and BSF (Table 2.1).

Table 2-1 Comparison of conventional slow sand filters and biosand filters, here supernatant depth and filtration rate vary over time in the BSF

	Conventional Slow Sand Filter [a]	**Biosand filter**
Sand depth	0.7 to 1.4 m	0.40 [b] to 0.55 m [c]
Effective media diameter (d_{10})	0.15 to 0.30 mm [a,d]	
Media uniformity coefficient (d_{60}/d_{10})	1.5 to 3.0 [a,d]	
Supernatant depth	1.0 to 1.5 m	0.28 to 0.02 m [b]
Hydraulic Operation	Constant flow rate or constant head	Falling head
Filtration rate	0.1 to 0.4 m/h	1.2 to 0.0 m/h [b] 4.0 to 0.0 m/h [d]
Residence Period	n/a	1 to 48 hours [c]

[a] (Huisman and Wood, 1974)

[b] (Elliott et al., 2006)

[c] (CAWST, 2012)

[d] (Kubare and Haarhoff, 2010)

Hydraulic operation

SSF are operated continuously, with water piped to the supernatant where it filters by gravity through the schmutzdecke, sand bed, and underdrain (Figure 2-2). Operation is controlled either with a constant flow rate, in which case the head above the sand surface increases with time as the filter becomes clogged, or with a constant head above the sand surface, in which case flow decreases as head loss increases within the filter over time (Crittenden et al., 2005).

Biosand filters, in contrast, are operated under a falling head regime. The entire filter dose is added at once. When the dose is first added to the filter, the difference between the supernatant depth and the filter outlet is at a maximum, as is the flow rate. As the dose of water filters through, the head difference reduces and the flow rate decreases until flow eventually stops (Kubare and Haarhoff, 2010).

Filtration rate

One consequence of the falling head flow regime is that maximum filtration rates are several times higher in BSF than in SSF (Table 2-1)

No widely accepted method exists for determining the maximum filtration rate in a BSF (Kubare and Haarhoff, 2010). The most common approximation method is volumetric, a calculation based on the time to filter the first litre of water (CAWST, 2009). A weakness of this method is that the filtration rate will have decreased over the course of filtering the set volume and so the maximum is likely to be underestimated (Kubare and Haarhoff, 2010).

A second method, proposed by Kubare and Haarhoff (2010), is to calculate the theoretical initial clean bed filtration rate using the Ergun equation (Crittenden et al., 2005):

$$h_L = [\kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3 g {d_{10}}^2} \frac{\mu}{\rho_w}] L v + [\kappa_I \frac{1-\varepsilon}{\varepsilon^3} \frac{L}{gd}] L v^2 \qquad (2\text{-}1)$$

where,

h_L = head loss across the media bed, m

κ_v = headloss coefficient due to viscous forces, unitless

ε = porosity, dimensionless

μ = dynamic viscosity of fluid, kg/m·s

L = depth of granular media, m

ν = superficial velocity (filtration rate), m/s

ρ_w = fluid density, kg/m^3

g = acceleration due to gravity, 9.81 m/s^2

d_{10} = effective media grain diameter, m

κ_I = head loss coefficient due to inertial forces, unitless

The first term of the Ergun equation describes the head loss component due to laminar flow, while the second term relates to turbulent flow. If purely laminar flow is assumed, the second term may be disregarded (Kubare and Haarhoff, 2010). In such a case, the remaining equation may be observed to simplify to the Darcy equation, where the bracketed term provides an approximation for the inverse of the initial hydraulic permeability:

$$\nu = k_p \frac{h_L}{L} \tag{2-2}$$

where,

k_p = coefficient of permeability, m/s

Crittendon et al. (2005) recommend a κ_v value of 110 to 115 for typical filter sand. Kubare and Haarhoff (2010), on the other hand, do not include κ_v in their description of the Ergun equation, and instead include a term they derived:

$$\frac{15}{\varphi^2} \cdot f(UC) \tag{2-3}$$

where,

φ = mean surface area sphericity, unitless

UC = uniformity coefficient (d_{60}/d_{10}), unitless

f(UC) = function of the uniformity coefficient, unitless

They provide a graphical solution to their uniformity coefficient function, which is dependent only on the media uniformity coefficient. Sphericity values for sand vary from 0.65 to 1.0, where a value of 1.0 would indicate perfect spheres (Huisman and Wood, 1974).

Huisman and Wood (1974) provide an alternative estimate of k_p for the design of slow sand filters:

$$k_p = 150\,(0.72 + 0.028\,T)\,\frac{\varepsilon^3}{(1-\varepsilon)^2}\,\varphi^2\psi^2{d_{10}}^2 \tag{2-4}$$

Where:

T = water temperature, °C

ψ = ratio between specific diameter and effective diameter, d_{10}

For low values of UC, as exist for both SSF and BSF (Table 2-1) values of ψ are estimated by the following relationship (Huisman and Wood, 1974):

$$1 + 2\log_{10} UC \tag{2-5}$$

One weakness of both the Huisman and Wood (1974) and Kubare and Haarhoff (2010) methods is that they require an estimate of grain sphericity. In a sensitivity analysis of this parameter, Kubare and Haarhoff (2010) demonstrated that increasing assumed sphericity from 0.7 to 0.9 resulted in an estimated initial filtration velocity increase of 65%.

None of the above methods for calculating the initial clean bed filtration rate have been tested experimentally on BSFs, as there is no method at present for measuring the instantaneous filtration rate. Consequently, they should be used with caution. As such, it is unclear whether the maximum filtration rates in BSF are close to 4.0 m/s, as stated by Kubare and Haarhoff (2010), or around 1.2 m/s as stated by Elliott et al. (2006) (Table 2-1).

Residence periods

To date, few studies on the BSF have investigated the effect of residence time on filter performance. Buzanis (1995) compared residence times of 24, 48, and 96 hours (1, 2, and 4 days). However, his measurements were on a fully ripened filter, and limited to hydraulic conductivity and effluent dissolved oxygen concentrations. Elliott (2009) dosed a fully ripened filter with 40 L after an 18-hr residence period, and then took effluent samples at 5 L increments to test for MS2 and PRD1 bacteriophage removal. His results indicated significant viral removal within the displaced pore water as compared to water which just ran through the filter without a residence period (Elliott, 2009). Jenkins et al. (2009) also found a significant improvement in the removal of fecal coliforms and MS2 with increasing residence time, but only compared time increments of 5 and 16 hours. In contrast, a study using longer residence time on fully ripened filters showed a 36 hour residence time to result in poorer removal of total coliforms than a 12 hour residence time, suggesting a negative impact of the longer residence time (Baumgartner et al., 2007).

Longer residence times are speculated to result in negative impacts on filter performance due to reduced dissolved oxygen (DO) and nutrient concentrations. A certain level of DO is necessary for healthy schmutzdecke development, and thus critical to the effective performance of the filter. As such, present recommendations are to dose the filter daily, with a maximum residence time of 48 hours (CAWST, 2009). Low dissolved oxygen may also cause poor taste and odour of effluent water and allow the re-dissolution of precipitated metals (Broder and Byron, 2005).

2.3 Research on BSF

2.3.1 Field testing of the BSF

Schmidt et al.'s (2009) critique of field studies on HWTS led to a range of high quality randomized control trials (RCT) and field studies on BSF in recent years (Table 2-2).

With the exception of Vanderzwaag et al.'s study (2009), continued usage rates for the filters was quite high (77%-94%). All studies found reductions in diarrhoeal disease (47%-61%), with one exception (Fabiszewski de Aceituno et al., 2012) where a trend was noted (39%) but did not reach statistical significance. *E. coli* removal directly by the filter was generally lower than that seen in laboratory studies (0.8 to 1.8 $\log_{10}$). A lower performance was observed when comparing the household's actual drinking water to that of control households (0.2 to 0.9 $\log_{10}$). This has been attributed to recontamination within the storage vessel (Fiore et al., 2010).

Some limitations of field studies to date include challenges regarding self-reporting bias. None of the studies included a placebo, which Schmidt et al. (2009a) stated should be required in their critique of HWTS studies, due to the logistical and ethical challenges of such an undertaking (Stauber et al., 2012b). Studies also do not include an objective measure of whether household water had been treated or not at the time of the household visit. It has also been suggested that BSF literature may show a higher level of publication bias than other treatments (Hunter, 2009).

Table 2-2 Summary of biosand filter field trials in peer-reviewed publications

Reference	Summary	DD reduction	Drinking water quality	Continued usage	Technology performance
(Stauber et al., 2012b)	RCT in Cambodia. 90 households with filter, 99 control households 8 month follow-up, biweekly visits Intervention households paid $10 for their filters	59%	0.8 $\log_{10}$ lower *E. coli* in household drinking water as compared to controls	89% of households said they used filter at least 3 times per week after 8 months	
(Fabiszewski de Aceituno et al., 2012)	RCT in Honduras. 90 households with filter, 86 control households 6 month follow-up, bi-weekly visits	39%, but not statistically significant	0.3 $\log_{10}$ lower *E. coli* in household drinking water as compared to controls		
(Aiken et al., 2011)	RCT in Dominican Republic, as well as follow-up study of a previous intervention. Differing follow-up times and sampling frequency Filters were free of charge	61%	0.9 $\log_{10}$ lower *E. coli* in household drinking water as compared to controls	90% after approx. 1 year	
(Fiore et al., 2010)	Convenience sample of 199 households in Nicaragua approx. 1 year after receiving filter		0.3 $\log_{10}$ lower *E. coli* in drinking water as compared to source water	77 % after 1 year	

(Tiwari et al., 2009)	RCT in Kenya, 30 households with a filter, 29 controls 6 month follow-up, monthly visits	54% for children,	0.5 $\log_{10}$ lower *E. coli* in household drinking water as compared to controls		1.25 $\log_{10}$ *E. coli* removal
(Stauber et al., 2009)	RCT in Dominican Republic, 75 BSF households vs. 79 control 6 month follow-up, weekly visits	47%	0.2 $\log_{10}$ lower *E. coli* in household drinking water as compared to controls		0.8 $\log_{10}$ *E. coli* removal (83%)
(Vanderzwaag et al., 2009)	Intervention follow-up in Nicaragua, after 3 or 8 years, 234 households			30% after 8 years, 7% after 3 years	1.36 ± 0.82 $\log_{10}$ *E. coli* removal
(Stauber et al., 2006)	Intervention follow-up in Dominican Republic, after 4 to 11 months, 55 households, one visit				1.15 $\log_{10}$ *E. coli* reduction, range of 0 to 2.5
(Duke et al., 2006)	Intervention follow-up in Haiti, after 1 to 5 years (average 2.5), 107 households, two visits per household			94% functioning and in use at time of first visit	1.8 $\log_{10}$ *E. coli* removal (98.5%)

2.3.2 Experimental studies on BSF

Early research on the BSF was slow and focussed on defining the technology and testing its performance at removing indicator microbes and physico-chemical parameters of interest (Elliott et al., 2006; Stauber et al., 2006). The BSF is effective at removing protozoan indicators, with >3.8 log removal of Giardia cysts and 3.7 log removal of Cryptosporidium oocysts (Palmateer et al., 1999). Results on the removal of bacterial indicators, primarily *E. coli*, were somewhat mixed when an entire filter run was considered, but improved over time with filter ripening, reaching averages of 1.9 $\log_{10}$ removal (Elliott et al., 2008). Results with viral indicators have been less impressive, with only an average of 0.5 $\log_{10}$ removal (Elliott et al., 2008).

Few studies have reported on effluent DO in BSFs. Of those that have, all suffer from the same limitation as Buzanis's study, in that the measurements were taken on samples from the filter outlet, which allows for aeration of effluent water before testing.

In a laboratory study on full-scale BSFs, Kennedy et al. (2012) found that average DO decreased from 6.17 mg/L at the influent to 2.47 to 3.10 mg/L at the effluent, but depended on the filter outlet diameter (Kennedy et al., 2012). They took composite samples in their study, that being mixed samples representing the full filter dose, as opposed to grab samples as Buzanis (1995) had done.

Chiew et al. (2009) noted that effluent DO from full scale iron-amended BSFs decreased to a mean of 0.5 mg/L with a range of 0.1-2.7 mg/L. Mean influent DO was not reported in that study. They concluded that although portions of the filter may have become oxygen deficient due to iron(II) oxidation or due to biofilms, the filter remained aerobic overall. This conclusion was based on their effluent DO samples remaining above 0 mg/L. (Chiew et al., 2009). However, aeration occurs at the BSF outlet before the collection of effluent samples, making it possible that water of 0.0 mg/L DO existed within the filter.

In a field study undertaken in Cambodia, Murphy et al. (2010) noted nitrification and denitrification occurring in BSF.

Nitrification is a microbially-mediated process which occurs in oxygen-rich environments, in which ammonia is converted first to nitrite, generally by the bacteria *Nitrosomonas*, then to nitrate, generally by *Nitrobacter*, according to the following steps:

$$2NH_3 + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2e^-$$

$$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$$

In contrast, denitrification generally occurs in oxygen-poor environments by heterotrophic bacteria. They convert nitrate to nitrogen gas, with nitrite as an intermediate product (Tchobanoglous et al., 2003).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Murphy et al. (2010) noted that in the filters where denitrification was observed, the influent was surface water with very low DO (1.8 to 2.5 mg/L). They do not report effluent DO in their study, but challenge Buzanis' DO assumptions by hypothesizing that significant oxygen was consumed in the schmutzdecke during the initial filtration period and that the deeper media bed was left anoxic during the residence period (Murphy et al., 2010b).

Since 2007, laboratory research on the BSF has focused on improving performance (Table 2-3).

A key finding was that the residence period is critical to viral removal (Elliott, 2009; Elliott et al., 2011) and recommendations were put forth to reduce dose volumes to ensure that water going through the filter remained within the filter for at least one residence period. As a result, the most recent construction guidelines for BSF have deeper media beds and smaller freeboards to limit dose volumes (CAWST, 2012).

Table 2-3 Select summary of experimental trials on BSF

Study	Parameter	Levels	Best performance
(Kennedy et al., 2012) Laboratory trials	Hydraulic loading rate	Modified outlet diameter at 0.5”, 0.37”, and 0.25”	no significant difference
(Jenkins et al., 2011; Jenkins et al., 2009) Laboratory trials	Loading head	10cm, 20cm, 30cm	smaller loading heads
	Residence time	5hr, 16hr	longer residence periods
	Sand diameter	0.17mm, 0.52mm	smaller sand diameter
(Elliott, 2009) Laboratory trial with full scale filters and columns, 3 replicates	Media	crushed granite, Accusand silica	no significant difference
	Residence time	4, 8, 16, 18, 20hr	longer residence periods
	Volume filtered	5, 10, 15, 20, 25, 30 L	< 0.7 pore volumes
(Vanderzwaag et al., 2009) field study with samples from filters in use [a]	Hydraulic loading rate	0 to 1.8 $m^3/m^2/hr$	lower hydraulic loading rate
	Standing head	1cm to 20cm	higher standing head
(Baumgartner et al., 2007) Laboratory trial, one ripened filter run under different scenarios [b]	Residence time	12hr, 36hr	shorter residence periods
	Volume filtered	10L and 20L, samples from 5L, 10L, 20L	10L dose better quality at 5L sample in all cases

[a]There may be confounding with hydraulic loading rate (as filters with higher standing heads would have limited space available to add water for dosing) and ripening stage (as lower standing heads would be associated with recent maintenance and schmutzdecke removal).

[b]Researchers noted a potential confounding factor of hydraulic loading rate

There is no consistent procedure at present for measuring the hydraulic loading rate. The filter operates under a falling head, and so the velocity peaks during initial loading then approaches zero as the run progresses. The peak velocity may be 3 or 4 times that of the average velocity (Kubare and Haarhoff, 2010). Other than the virus studies by Elliott et al. (2008, 2009), no other BSF studies have included sample ports within the columns, though the results from Baumgartner et al. (2007) with effluent grab samples suggest that different treatment efficiencies were associated with residence at different areas within the water column.

More recent laboratory research has focussed on iron-amendments of filter media to improve microbial (Ahammed and Davra, 2011; Bradley et al., 2011; Noubactep et al., 2012), and arsenic removal rates (Chiew et al., 2009; Ngai et al., 2007). Other media amendments have also been tested to improve performance (Baig et al., 2011) and affordability (Ghebremichael et al., 2012)

2.4 Knowledge gaps

Despite advances in environmental health engineering, large questions still remain, including:

- Risk factors for diarrhoeal disease in particular regions
- Sustainability and consumer acceptance of household water treatment technologies
- Differences between continuous and intermittent operation of filters with the same sand and supernatant depths, especially in regards to DO
- Impact of increased residence times on the filter's ability to develop a schmutzdecke and remove bacterial indicators.

The following chapters extend the existing knowledge on these issues.

2.5 Connecting text to chapter 3

This chapter identifies the baseline conditions in the village of St. Cuthbert's, Guyana, as related to drinking water. The chapter looks at both the physical aspects of source and household water quality, as well as the cultural aspects of knowledge, attitudes, and practices relating to water, sanitation, and hygiene.

This chapter was prepared as a manuscript to be submitted to a peer-reviewed journal in 2013. It was co-authored by Dr. Chandra Madramootoo, who supervised the work, and Savitri Jettoo of Guyana Water Inc., who assisted with the study design and provided editorial feedback. All literature cited in this manuscript is listed at the end of this thesis.

CHAPTER 3 Water, Sanitation, and Hygiene in a Guyanese Amerindian community

3.1 Abstract

The risk factors for diarrhoeal disease amongst Amerindian communities in Guyana are poorly understood. This study used source water sampling; a knowledge, attitudes, and practices questionnaire; and a household water sampling campaign in order to identify the key risk factors for diarrhoeal disease in St. Cuthbert's, Guyana.

Surface water sources had thermotolerant coliform loads consistent with a "high" level of risk (100-1000 cfus/100mL), while water from standpipes was of "low" risk (<10 cfus/100mL). However, most households (59%) had drinking water of "very high risk" (>1000 cfus/100mL) regardless of the source.

Risk factors for diarrhoeal disease were serving water by scooping as opposed to pouring (exp $\beta = 4.221$), listing "after eating" as a critical hand-washing time (exp $\beta = 2.607$), and being an extended household (exp $\beta = 3.670$). Mitigating factors were having water piped to the compound (exp $\beta = 0.093$) and answering the question "What causes diarrhoeal disease" with a reference to poor personal hygiene, such as not washing hands (exp $\beta = 0.347$).

The main risk factor for having poor drinking water quality was storing water in a container with a wide mouth and serving by scooping from it (exp $\beta = 0.110$). Factors reducing risk included having water piped directly to the compound (exp $\beta = 3.020$), and having children under 5 years old in the household (exp $\beta = 3.079$).

3.2 Introduction

The under-five mortality rate in Guyana (62 per 1000) is the second highest in Latin America and the Caribbean, after Haiti. Diarrhoeal diseases are the third leading cause of under-five mortality, behind only pneumonia and prematurity, and are responsible for 15% of child deaths. In Guyana this represents double the child deaths attributed to HIV, malaria, and measles combined (WHO, 2010). Approximately 88% of diarrhœa is attributed to preventable fecal-oral infections (Pruss-Ustin et al., 2004). The primary means of breaking fecal-oral transmission pathways include: adequate sanitation, good personal and domestic hygiene, sufficient quantities of water, and safe drinking water (Fewtrell et al., 2005).

Millennium Development Goal #7, "to ensure environmental sustainability," includes the target of halving the proportion of people in the world without access to improved drinking water (WHO and UNICEF, 2010). An improved water source is defined as a public standpipe, treated piped water, borehole, tube well, protected spring, protected dug well, or rain. Studies on historic mortality patterns in the U.S. have attributed a decline of three-quarters of infant mortality and two-thirds of child mortality between the nineteenth and twentieth centuries to improved access to clean water (Cutler and Miller, 2005). In a meta-analysis in the early 1990's, improvements to drinking water quality at the source led to a median reduction in diarrhoeal disease rates of 17% (Esrey et al., 1991). However, water collected from a low risk source is not necessarily low risk at the time of consumption. The processes of collecting, transporting, and storing water can decrease drinking water quality (Sobsey, 2002). This post-collection contamination can be significant in some settings (Wright et al., 2004).

If a population is exposed to multiple transmission pathways for pathogens, high rates of diarrhoea may continue even if the primary path is eliminated, unless the additional exposure routes are also mitigated (Briscoe, 1984). Therefore, while breaking one part of the transmission chain [e.g., water quality improvements (Clasen et al., 2007)] could result in direct health improvements, a multi-barrier approach is the most effective strategy (Eisenberg et al., 2007; Gundry et al., 2004; Vanderslice and Briscoe, 1995). Such an approach tackles sanitation, hygiene, and water quantity and quality in a holistic manner. However, implementing multiple campaigns may cause confusion and exhaust the attention and interest of the target population (Curtis et al., 2000). As an intervention is only effective if it reduces an active (*vs.* potential) transmission pathway, interventions of all types may not be necessary for all communities. Thus, a sanitation intervention will be ineffective if the community's existing sanitation practices do not significantly expose residents to fecal pathogens. Consequently, a thorough study of a community's practices and the identification of potential exposure routes are necessary before planning an intervention if it is to be effective in reducing transmission risks.

On a national scale, Guyana has 81% access to improved sanitation, which is comparable to the rest of the Latin and Caribbean region at 80% (United Nations, 2011). Guyana has already exceeded its Millennium Development Goal target for access to improved drinking water, having achieved 94% coverage (WHO, 2010). However, these improvements have primarily occurred along the coast. In the inland 'hinterland' region, as of 2002, only 11% of households had access to an improved water source (Government of Guyana, 2007). Guyana's Poverty Reduction Strategy (Government of Guyana, 2002) recognized the pressing need to address the concerns of the hinterland region, but poor accessibility and low population density make improving environmental health infrastructure in hinterland communities challenging. Though they only make up 9% of the country's total population, the majority ethnic group in the Guyanese hinterlands is Amerindian (Beaie, 2007). Little is known about the knowledge and practices of this group in regards to risk factors for diarrhoeal disease.

The purpose of this study was to investigate the environmental risk factors for diarrhoeal disease in a Guyanese Amerindian community in terms of water, sanitation, and hygiene; to evaluate the quality of source waters used for drinking by residents; and to identify risk factors for poor household drinking water quality. The scope of this study was limited in that it included only one visit per household for the collection of diarrhoeal incidence data that depended on two-week recall, and collected only one water sample per household. Within these limitations, this study provides an informative snapshot of risk factors in this community.

3.3 Materials and Methods

3.3.1 Study Area

Guyana's climate is tropical, with the northern, coastal region of the country where St. Cuthbert's is located experiencing two wet seasons annually, generally from April to July and again from November to January. The annual rainfall measured at the local gauging station for 2008 was 2706 mm, while for 2009 it was 1890 mm.

St. Cuthbert's is an Arawak community along the Mahaica River in Guyana, straddling the two regions of Demerara-Mahaica (Region 4) and Mahaica-Berbice (Region 5). McGill University has a long-standing relationship with St. Cuthbert's through the Caribbean Water Initiative (CARIWIN, 2011). Data from the Ministry of Amerindian Affairs place the population of the village at 1243, making it the seventh largest Amerindian community in Guyana. It is approximately 80 km from Georgetown, the capital of Guyana. Residents generate income through shift work for mining companies outside the village, remittances, farming, selling of arts and crafts, and logging. They also practice subsistence agriculture, hunting, and fishing. St. Cuthbert's has a health centre and schooling up to the secondary level.

Staff at the local health centre listed diarrhoea as one of the top health issues in the community. The health centre casebook recorded a median of three visits per week for gastroenteritis symptoms between March 2007 and July 2009 (first and third quartiles of one and six). However, because residents often treat diarrhoea at home, or choose to visit doctors outside the village rather than use the local clinic, the actual rate of diarrhoea would be significantly above that recorded.

Food for the Poor, an international non-governmental organization, developed a residential project within the community in 2004. This project included 40 houses, each with a pour flush latrine draining to a septic tank, as well as a small concrete-floored hut for bathing which drains to the yard. Food for the Poor also installed two wells with hand pumps in the village, but both had been abandoned before the onset of this study.

At the time of the study, the community had one central borehole, approximately 150 m deep, with a solar powered pump filling a series of elevated tanks. Each day the local operator would allow the tanks to fill completely before opening the valve to the gravity-fed distribution system. The system supplied ten public standpipes (Figure A-1) and approximately 40 private yard or house taps. Water was available for two to six hours per day.

Rainwater collection systems in the community varied from elaborate structures with guttering and 300 L tanks on elevated trestles, to informal systems of buckets placed on porches.

The local assistant identified six locations on local creeks that were used frequently by members of the community for water collection (Figure A-2). Of these, three were on the Mahaica River: Landing, Barabara, and Shebidiah, while three were on tributary creeks: Kunabali Creek, Taylor Creek, and the headwaters of Korkobani Creek (Figure 3-1).

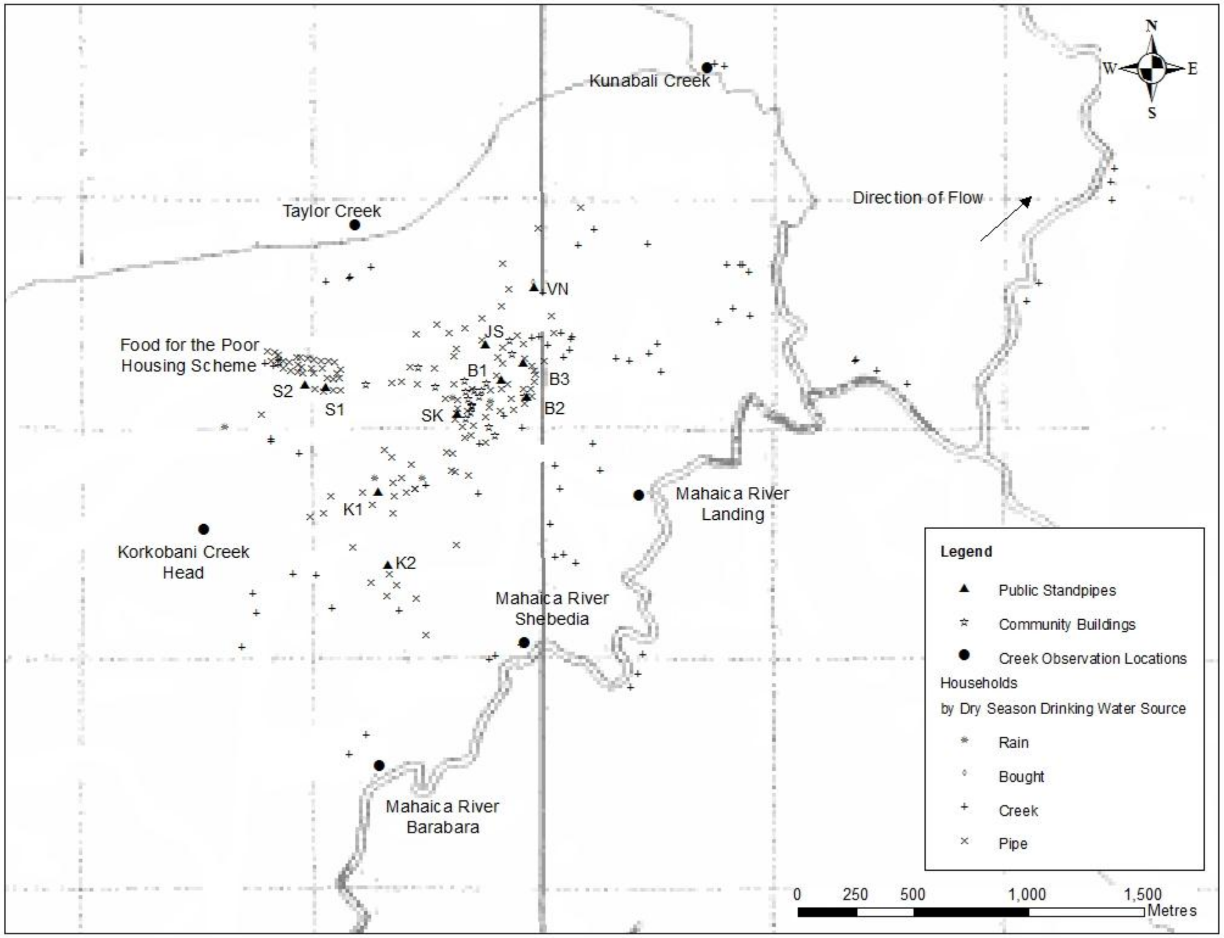

Figure 3-1 Map of St. Cuthbert's showing creek observation locations, standpipes, and households by dry season drinking water source

3.3.2 Study Structure

Prior to the study, key members of the community, including the elected community leader, health centre staff, and local water system operator, were interviewed to develop a background understanding of specific health, water, sanitation, and hygiene issues.

The study consisted of three distinct sections, further described below. The first was a sampling program of the source waters in the community. The second was a questionnaire about water, hygiene, sanitation, and health. The third was a sampling program for household drinking water quality.

Part 1: Source Water

Source water samples were collected from the public standpipes and surface water collection points approximately fortnightly from the end of August 2008 until the beginning of December 2008, resulting in nine samples from each source. Three supplementary samples were added for each site during the wetter period from late May to early July of 2009.

Observers spent two days at each source observing the different uses of the source and taking hourly samples for temperature, turbidity, pH, electro-conductivity, and total dissolved solids. Surface source locations were observed from 6:00 to 17:30 (dusk), while standpipe locations were sampled from the start to end of water availability (two to six hours). One observation day for each location was during the dry season, while the second was during the wet season.

Part 2: Questionnaire

The second part of the study consisted of a knowledge, attitudes, and practices survey regarding water, sanitation, hygiene, and supporting demographic and socio-economic information. The questionnaire was implemented from July to December of 2008. It included yes/no, multiple-choice, and open-ended questions. Respondents were also asked about incidences of diarrhoea in their household over the previous two weeks. This study defined diarrhoea as the passing of three or more loose or liquid stools over a 24-hour period.

At the time of the visit, enumerators observed the household sanitation facilities, confirmed drinking water storage methods, checked for the presence of soap at the designated hand washing site, and recorded the GPS coordinates of the household. The locations of community standpipes were also mapped using GPS, and the distance from each house to the nearest standpipe was calculated.

The survey was modified to improve the wording and relevance of the questions after it was piloted on three households in the village. Every household in St. Cuthbert's was approached. Only one person per household could participate, and respondents were required to be older than 18 years of age. Several households were excluded from the study because household members were not home during repeat visits, were out working for an extended time, or were all under the age of 18.

A wealth index was derived using principal components analysis (PCA) on socio-economic data collected in the questionnaire (Vyas and Kumaranayake, 2006). The variables included in this analysis were access to electricity; roofing material (thatch versus corrugated metal); wall material (wood versus concrete); and ownership of a television, phone, radio, bicycle, and a gas or kerosene stove. Also included as ordinal variables were the furthest place travelled by the respondent (other country, other region, or other community within the region/no travel) and the most recent travel outside of the community (more than one year or never, more than one month, more than one week, or less than one week). The PCA excluded hygiene, sanitation, and water infrastructure indicators, which were analyzed separately.

Part 3: Household water

Household samples were collected in March and April of 2009. All households within the community were approached for this study, including those located beyond the central village.

Each respondent provided a 250 mL sample of their household drinking water, which they collected as if they were about to take a drink. Respondents provided this sample in a drinking water cup from the household, from which approximately 100 mL was poured from the cup into a sterile sample bag for microbiological analysis, with the remaining water used for *in-situ* analysis of physical parameters. They also answered a general survey about their household. Participants were given a calendar on which to record diarrhoeal disease incidents in the household over a one-month period. However, compliance for this was low (30%, 59/198) and no further analysis was conducted on this data.

During the follow-up visit to collect the calendars, enumerators inspected sanitation facilities and administered a small survey for socio-economic indicators.

The indicators collected for calculation of the household wealth index for this portion of the study were slightly modified from the initial questionnaire. The indicators included having access to electricity, and owning a fridge or freezer, cell phone, sofa or chair with cushions, bed with a mattress, motorcycle, vehicle, television, radio, and store. Other variables included house roofing material (corrugated metal versus thatch), wall material (concrete versus wood), and the primary type of stove used in the household (gas, kerosene, or wood). As with the initial questionnaire, hygiene, sanitation, and water indicators were not included in the PCA, as their effects were analyzed separately.

3.3.3 Water quality

Thermotolerant coliform (TTC) colony forming units (cfu) acted as a microbiological indicator of fecal contamination in this study. Source water samples were collected in sterilized 500 mL plastic sample bottles. Household samples were poured from the household's cup into a sterile Whirl-Pak bag (NASCO Corp., Fort Atkinson, WI). Samples were transported to the field laboratory in a sample cooler and processed within 6 hours. TTC were enumerated with the Oxfam DelAgua kit (University of Surrey, 2004), using the membrane filtration method with methyl laurel sulphate broth on an absorbent pad as a growth substrate. A pressure pot was used to sterilize sample bottles, Petri dishes, and other materials in the field (University of Surrey, 2004). Sterilization of the filter funnel between samples was done by boiling (Parker et al., 2010). Samples were placed in the field incubator and allowed to acclimatize for 2 hours, before incubation for 16 hours at 44 ± 0.5°C. Blanks were run with locally purchased mineral water that was labeled as having been UV disinfected.

The sample type determined the volume of sample that was filtered, with 100 mL for standpipes and 10 mL for household samples and creek water. This led to a possible detection range of 1 to 100 cfu per 100 mL for standpipe water, and ten to 1000 cfu per 100 mL for surface and household samples.

The risk classification system used for interpreting the TTC results was based on the suggested system by the World Health Organization (WHO), which is summarized in Table 3-1 (WHO, 1997). Thermotolerant coliforms are indicators of possible fecal contamination of the water source. As they generally inhabit the gut of animals, their presence indicates that the water may have been exposed to feces and thus may contain pathogens that are present in feces.

Table 3-1 Risk classification system for thermotolerant coliform levels in drinking water

Thermotolerant Coliforms	Risk Level
0 cfu/100 mL	Meets WHO standards
1-10 cfu/100 mL	Low Risk
11-100 cfu/100 mL	Intermediate Risk
101-1000 cfu/100 mL	High Risk
>1000 cfu/100 mL	Very High Risk

Turbidity was measured *in-situ* using a Lamotte 2020e handheld turbidimeter (Lamotte Company, Chesterton, MD). Temperature, electrical conductivity (EC), pH, total dissolved solids (TDS), and dissolved oxygen (DO) were measured *in-situ* using a YSI 556 multimeter (YSI Inc., Yellow Springs, OH).

3.3.4 Data analysis

The data collected in the questionnaire were primarily categorical or binomial (yes/no). This data were analyzed using the two-tailed Pearson Chi-Square or the Fisher's Exact Test, as appropriate. Odds ratios were calculated for binomial factors to indicate potential relationships between collected variables and the presence or absence of diarrhoea within the household over the previous two weeks. Quantitative variables were analyzed using t-tests.

For the household water quality analysis, households were classified as either low to intermediate risk (<= 100 cfu/100 mL), or of high to very high risk (> 100 cfu/100 mL) for analysis. Odds ratios and significance levels were calculated first for individual covariates, and then adjusted for all other covariates in a binary logistic analysis.

For logistic regression models, the backward elimination likelihood-ratio (LR) method was used with a cut-off *p* value of 0.10. The models were tested for goodness of fit and performance using the Hosmer–Lemeshow statistic and by analyzing the receiver operating curve (Kleinbaum and Klein, 2010). Logistic regression models are of the following form:

$$\pi(x) = \frac{e^{\beta_o + \beta_i x_i}}{1 + e^{\beta_o + \beta_i x_i}}$$

Where $\pi(x)$ is a number between 0 and 1 representing the conditional probability of the outcome of interest, β_i are the equation parameters, and x_i are the covariates.

Source water quality parameters had repeated measures and did not follow a normal distribution, so generalized linear mixed modeling was used to analyze these results (Gbur et al., 2012).

TTC results of source samples were periodically either below or above the detection limits of the analysis used, known as data "censoring". This parameter was analyzed using the nonparametric generalized-Wilcoxon score tests to account for the uncertainty surrounding the censored data (Helsel, 2005).

The statistical software used for the analysis was PASW Statistics 18 (IBM; Somers, New York; www.spss.com).

3.3.5 Ethics

The Guyanese Minister of Amerindian Affairs was briefed and approved the project before it began, as was the village leader. This study protocol for the initial survey was approved by the Research Ethics Board of the Faculty of Agricultural and Environmental Sciences at McGill University, Quebec, Canada, protocol number 915-0608, June 18, 2008. The study protocol for the household water testing was reviewed and the protocol approved by the Institutional Review Board in the Faculty of Medicine at McGill University (Study # A02-E01-09A).

Residents who volunteered to be part of the study had a consent form read to them, which they signed before being surveyed or sampled, and of which they received a copy. Residents were permitted to skip questions that they did not wish to answer. Only one person per household was interviewed for each part of the study, and consent forms were only accepted if the respondent was over 18 years of age.

Households did not receive any financial or material incentive to participate in the questionnaire or in the household water sampling.

3.4 Results

3.4.1 Source water

Surface Water

All six of the surface water locations sampled were high risk, with median TTC greater than 100 cfu/100mL. The maximum value for each site was above the detection limit of 1000 cfu per 100mL (Figure 3-2). Neither Kunabali Creek nor Taylor Creek had any sample with TTC below 100 cfu/100mL.

The remaining water quality parameters were consistent with those of literature values for "black water" rivers and creeks in the neighbouring Amazon river basin, so named for the distinctive colour given by tannins and humic acids, (Junk and Piedade, 2005). Although colour was not measured in this sampling program, surface water was noted to have a distinct reddish colour, similar to weak tea. The water from all of the surface sources was of low turbidity (mean < 5 NTU), low conductivity and dissolved solids, and very low pH (Table 3-2). The range of pH in surface water was 3.11 to 4.21. Although the World Health Organization (WHO) drinking water quality guidelines note that pH is an important operational parameter (WHO, 2011), they do not provide a limit for human health. Previous versions of the guidelines did include an optimum operational range for pH of 6.5 to 9.5. However, this was not health-based and it was noted that a broader pH range is acceptable in the absence of a distribution system (WHO, 2008).

Temperature varied significantly between the surface sources ($p < 0.001$). Taylor Creek, in a forested area, was the coolest at a median of 25.6°C while the sample point on Korkobani Creek, in the savannah, was the warmest at 28.1°C (Table 3-2). Korkobani Creek also had the lowest average DO in this sampling program, at 3.8 mg/L (Table 3-2). This may have been due to the location of the collection point at the creek "head", or spring. Although low DO can cause water to taste flat (Government of British Columbia, 1997) and can be limiting for aquatic life, there is no WHO guideline for this parameter for drinking water.

Most observed surface water usage events were not for water collection (41 events), but rather for bathing (160 events). Other observed uses included: boat transportation (36 events), washing kitchen wares (26 events), recreation/playing/swimming (25 events), washing clothes (22 events), and fishing (9 events). Mahaica River – Landing was the most utilized location (108 events of which ten were water collection), which may explain its higher TTC and turbidity as compared with the two other sampling points on the same river.

The only water quality parameter which varied over the course of the day was temperature, which rose a mean of 1.3°C (σ = 0.8°C) from a minimum temperature at 6:00 to a maximum at approximately 15:00. Temperature was also the only parameter to vary significantly between dry and wet periods (p=0.014).

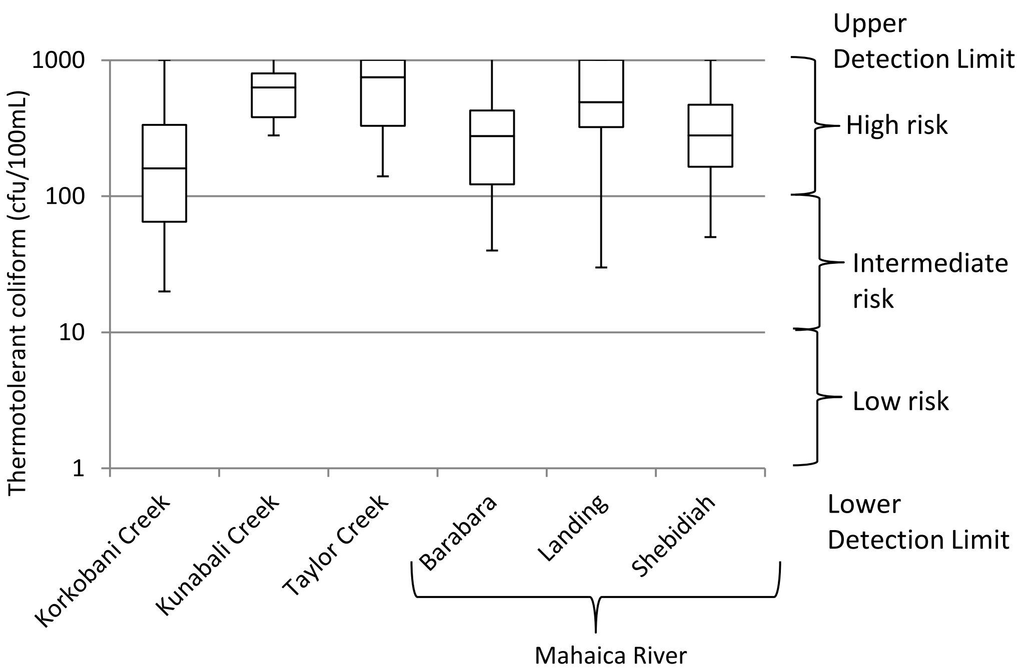

Figure 3-2 Thermotolerant coliforms in Surface water samples

Ground water

For eight of the ten standpipes, median TTC met WHO standards and were below the detection limit of 1 cfu/per 100mL. However, all but one standpipe had at least one sample above ten cfu/100mL, in the intermediate risk category (Figure 3-3).

None of the standpipes had any turbidity sample exceed five NTU. The maximum recorded turbidity was 3.38 NTU, but the median was only 0.2 NTU. The standpipe pH was higher than that of the creeks, but was still acidic at a median of 4.5 (Table 3-2). The temperature of the standpipe water was higher than that of the creeks, with an overall median of 29.3°C, with one sample reaching 33.8°C. This result was consistent with user perceptions, as the higher standpipe temperature was a reason some respondents volunteered for preferring creek water.

Table 3-2 Summary of water quality parameters at source. Median with interquartile range in brackets

	Kunabali Creek	Korkobani Creek	Taylor Creek	Mahaica Barabara	Mahaica Landing	Mahaica Shebidiah	Standpipes
TTC, cfu/100mL	630 (380-800)	160 (65-335)	750 (330- >1000)	278 (123-428)	490 (323- >1000)	280 (165-470)	1 (0-4)
Turbidity, NTU	4.1 (2.1-4.7)	0.5 (0.4-0.8)	1.0 (0.8-1.3)	1.2 (1.0-1.4)	2.0 (1.5-2.4)	1.7 (1.1-2.4)	0.2 (0.1-0.4)
pH	3.7 (3.6-3.8)	3.8 (3.7-4.1)	3.6 (3.4-3.9)	3.6 (3.3-3.8)	3.7 (3.5-3.8)	3.8 (3.5-3.9)	4.5 (4.3-4.7)
EC, µS/cm	35 (33-36)	29 (27-32)	37 (36-37)	47 (45-49)	46 (44-48)	46 (44-48)	17 (16-18)
Temp, ^{0}C	26.6 (26.4-27.2)	28.1 (27.2-28.4)	25.6 (25.5-25.8)	25.7 (25.4-26.0)	26.1 (25.6-26.4)	25.9 (25.7-26.3)	29.3 (28.3-29.9)
DO, mg/L	5.2 (4.5-5.8)	3.5 (2.9-4.3)	3.6 (3.4-3.9)	5.6 (4.7-5.7)	5.8 (5.1-6.8)	5.9 (5.1-6.0)	5.5 (4.3-4.7)

All observed uses of the standpipe water were for water collection, though people would also meet and socialize at standpipes. The ten standpipes were used with different frequencies, with S1 having 86 collection events over the two observation days, in contrast to K1, which had only three. For higher use standpipes, a queue of buckets would form before the water was available. The person who brought and filled the containers was not always the person who collected the filled containers (29 observed cases). For example, a young child might fill the buckets while the water was available, and an older sibling or parent might then collect the heavy containers after school or later in the day.

Water quality parameters remained stable from hour to hour over the course of the day. Electrical-conductivity ($p = 0.0003$) and TTC ($p = 0.002$) were found to vary between wet and dry periods, with the wetter period having slightly lower electrical-conductivity and TTC. This may also have been due to other factors, such as system maintenance between the dry and wet period sampling, as opposed to seasonal influences.

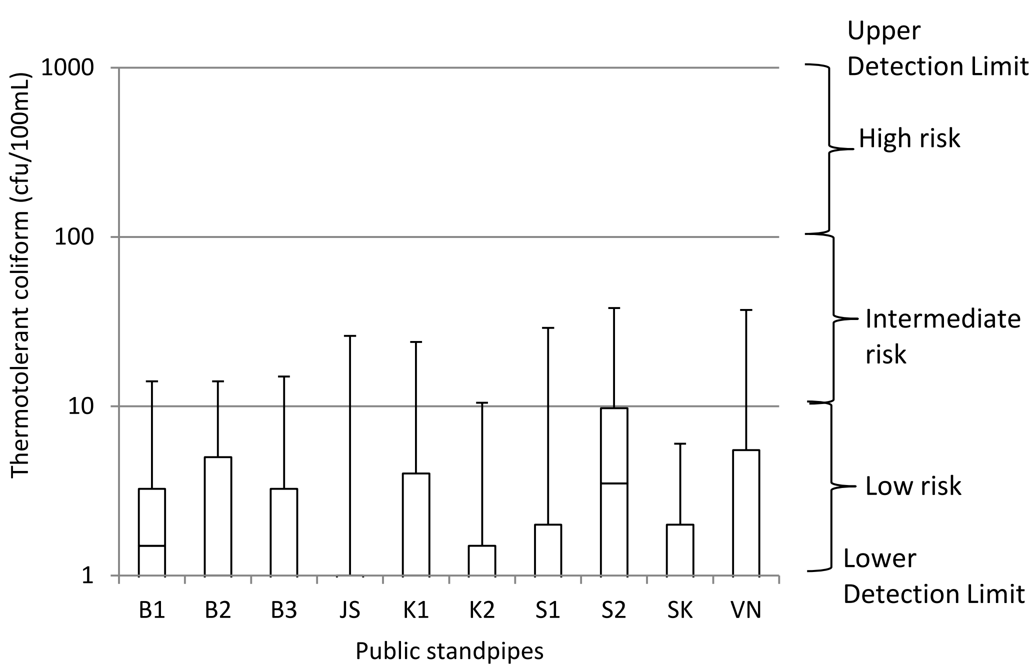

Figure 3-3 Thermotolerant coliforms in standpipe samples

3.4.2 Questionnaire

One hundred and ninety-eight households participated in the initial survey. The mean age of the respondents was 42.7 (σ = 15.6), and 74% of the respondents were female. Altogether, the surveyed households represented 945 people (76% of the estimated 1243 residents).

Diarrhoeal Disease Prevalence

Twenty-one percent of households had at least one person who had experienced diarrhoea over the two weeks prior to the survey (

Table 3-3). In these households, the median was two members having been ill, with a range of one to nine. The number of cases of diarrhoea or gastroenteritis registered at the health clinic during the time of the study (July to December 2008) was similar to the rest of the period on record (March 2007 to July 2009).

Although most respondents did not believe that diarrhoeal diseases were a big problem in the community for adults (

Table 3-3), they did identify them as a big problem for children, with 75% of respondents having known someone who either died of, or lost a child to, diarrhoeal disease. Of the 85 reported diarrhœa incidents in this study, 24 (28%) were for children aged five and under, including 11 (13%) which were for children aged two and under (Figure 3-4).

The survey included two open-ended questions about causes and prevention of diarrhoea. Households whose answer included personal hygiene or hand washing in at least one of these were marginally less likely to have had a diarrhoea case (p = 0.099).

Table 3-3 Questionnaire responses related to diarrhoeal disease

Variable	Total Responses	Yes	%
Has any member of this household had diarrhoeal disease in the last 2 weeks?	198		
Yes		41	21%
No		157	79%
Is diarrhœa a problem for adults in the community?	196		
A big problem		59	30%
Somewhat of a problem		82	42%
Not really a problem		55	28%
Is diarrhœa a problem for children in the community?	196		
A big problem		167	85%
Somewhat of a problem		20	10%
Not really a problem		9	5%
I know someone who died or lost a child because of diarrhoeal disease	195		
Agree		146	75%
Disagree		36	18%
No response		13	7%

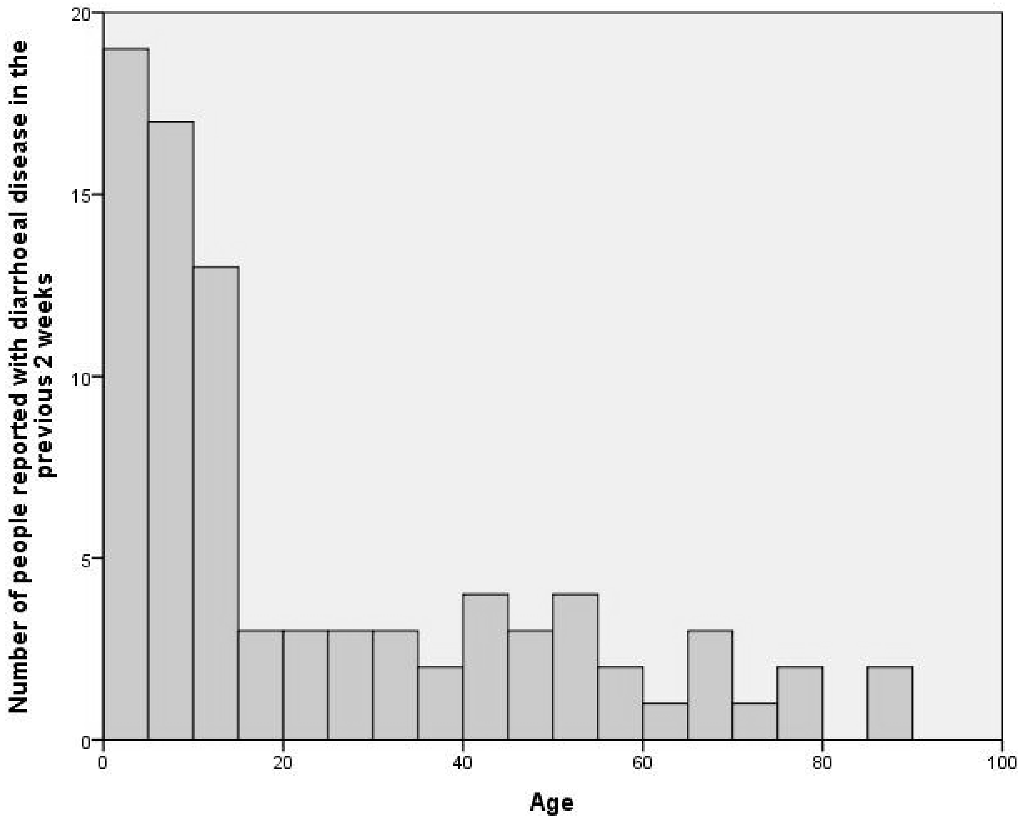

Figure 3-4 Diarrhoeal disease incidents over the two weeks prior to the survey, by age

Demographics

Every male and female head of household in this study had at least some primary school education. Five women and 11 men had education up to the tertiary level.

Most households (82%) included at least one child. Of the residents represented by the survey, 150 (16%) were aged five or under, with a mean household size of 4.8 (σ = 2.1). In 76 households (38%), one partner was usually living elsewhere (generally due to shift work).

Households were initially classified into several categories for family type, such as childless, extended, two-parent, single parent, or two-parent where one parent was mostly away. However, only extended families were significantly different, so the other categories were combined. Extended families were significantly more likely to have had a case of diarrhoea (*p*=0.005) (Table 3-4). The number of people in the household was marginally significant (*p*=0.077).

The first component of the principal component analysis explained 29% of variance, which is within the range noted by Vyas and Kumaranayake (2006). This component was taken as the household wealth index (Houweling et al., 2003). The distribution was left skewed and exhibited some clumping and truncation, indicating that the selected variables performed better at differentiating households with lower wealth indices than with higher. Wealth index was marginally significant (*p*=0.065).

Table 3-4 Results of unadjusted and adjusted binary logistic analysis of selected questionnaire responses and diarrhoeal disease where exp β <1 indicates reduced likelihood of having had a diarrhoea incident in the household, and exp β >1 indicates increased likelihood

	No diarrhoeal disease	With diarrhoeal disease	Unadjusted		Adjusted	
Variable			**exp β (95% CI)**	**p value**	**exp β (95% CI)**	***p* value**
DEMOGRAPHIC DATA						
Household type				0.005		0.009
Extended family	30	16	2.767 (1.330-5.757)		4.667 (1.466-14.852)	
Other family type	127	25				
Any children under five in this household				0.517		0.570
yes	83	24	1.259 (0.628-2.524)		1.381 (0.454-4.198)	
no	74	17				
Any school age children (ages 5-17) in this household				0.185		0.957
Yes	110	33	1.763 (0.757-4.101)		0.965 (0.262-3.558)	
no	47	8				
Female highest schooling				1.000		0.937
some primary	131	36	0.910 (0.286-2.891)		0.911 (0.092-9.016)	
some secondary or tertiary	16	4				

Variable	No diarrhoeal disease	With diarrhoeal disease	Unadjusted exp β (95% CI)	p value	Adjusted exp β (95% CI)	*p* value
Male highest schooling				0.955		0.248
some primary	124	33	0.974 (0.390-2.434)		2.977 (0.468-18.954)	
some secondary or tertiary	27	7				
DIARRHŒAL DISEASE						
What causes diarrhoeal disease (open-ended question - 194 responses)?						
Untidiness, garbage	74	14	0.582 (0.284-1.192)	0.136	0.738 (0.262-2.075)	0.564
Poor personal hygiene	33	3	0.406 (0.135-1.221)	0.099	0.097 (0.016-0.591)	0.011
Water	127	37	2.185 (0.723-6.601)	0.157	0.624 (0.121-3.222)	0.573
Food (e.g., dirty fruits, flies, stale)	33	11	1.378 (0.625-3.037)	0.426	1.653 (0.444-6.152)	0.453
Poor sanitation	13	3	0.874 (0.237-3.226)	1.000	0.765 (0.090-6.480)	0.806
Seasonal (rainy /dry/inter-season)	92	26	1.225 (0.602-2.492)	0.576	2.404 (0.774-7.470)	0.129
HYGIENE						
Enumerator observed soap at the designated hand washing location				0.211		0.174
Yes	78	16	0.640 (0.317-1.291)		0.407 (0.111-1.489)	
No	78	25				

Variable	No diarrhoeal disease	With diarrhoea l disease	Unadjusted exp β (95% CI)	p value	Adjusted exp β (95% CI)	*p* value
When do you usually wash your hands? (open ended question - 198 responses)						
After toilet	137	33	0.602 (0.244-1.487)	0.268	0.440 (0.103– 1.885)	0.268
Before eating	108	34	2.204 (0.913-5.317)	0.073	2.167 (0.628-7.477)	0.221
After eating	100	33	2.351 (1.017-5.436)	0.041	1.996 (0.550-7.245)	0.293
After working/ yard work/ cleaning	56	14	0.935 (0.454-1.928)	0.856	0.945 (0.330-2.700)	0.915
Before cooking/ preparing foods	45	11	0.913 (0.421-1.976)	0.816	0.291 (0.078-1.091)	0.067
SANITATION						
Private/Shared				0.862		0.752
Private (single household)	130	34	1.090 (0.414-2.868)		0.797 (0.196-3.247)	
Shared (multiple households)	25	6				
Type of toilet (compared to Bush toilet or none)						
Bush toilet or none	5	2				0.790
Pit latrine	117	29				
Pour flush toilet	29	10				
Pipe flush toilet	6	0				

Variable	No diarrhoeal disease	With diarrhoeal disease	Unadjusted exp β (95% CI)	p value	Adjusted exp β (95% CI)	*p* value
Enumerator observed that toilet seat and bowl were clean from fecal matter				0.088		0.608
Yes	128	28	0.481 (0.205-1.128)		0.698 (0.177-2.752)	
No	22	10				
Additional enumerator comments (open ended - 190 observations)						
Paper present	19	5	0.992 (0.346-2.845)	0.989	0.974 (0.156-6.099)	0.978
Toilet covered	12	6	2.044 (0.716-5.837)	0.220	14.497 (1.721-122.093)	0.014
In need of repair	35	12	1.420 (0.655-3.082)	0.373	1.598 (0.451-5.658)	0.468
WATER						
Pipe to house or yard				0.004		0.125
Yes	34	1	0.090 (0.012-0.682)		0.152 (0.014-1.683)	
No	123	40				
Do you ever boil or treat your water before using it?				0.267		0.074
Yes	69	22	1.477 (0.741-2.944)		2.675 (0.909-7.871)	
No	88	19				

Variable	No diarrhoeal disease	With diarrhoeal disease	Unadjusted exp β (95% CI)	p value	Adjusted exp β (95% CI)	*p* value
Drinking water serving method				0.050		0.198
Scoop from container	127	39	3.992 (0.907-17.578)		3.305 (0.535-20.417)	
Other (e.g. pour, tap)	26	2				
Primary drinking water source through the year				0.760		0.955
Pipe	55	12				
Rain (or pipe plus rain)	40	12				
Creek (or rain or pipe plus creek)	61	17				

Hygiene

Nearly all (196/198, 99%) respondents said that they washed their hands with soap, but only 48% had soap at their hand washing site during the inspection (Table 3-4). The soap was frequently in the form of powdered laundry detergent. Reasons given for not keeping soap at the hand washing site included the possibility of dogs getting into it, children taking it and not returning it, or theft.

In an open-ended question about when they would wash their hands, households whose response included "after eating" were at significantly higher risk ($p = 0.041$). "Before eating" was marginally significant in increasing risk ($p = 0.073$) (Table 3-4).

Water

Access to improved water sources varied through the community, with eight households having water piped directly into their home, but with 15 located more than one kilometre from the nearest standpipe.

Most households within 100 m of a standpipe used it as their primary drinking water source in the dry season, with only one choosing creek water and a second listing creek plus pipe (Figure 3-5a). However, by 300 m to 400 m from the nearest standpipe, more than half of respondents listed creek water among their primary drinking water sources. By 400 m from the nearest standpipe, no household listed pipe water. In the dry season, five households identified rainwater as their primary source, with three others listing rain plus pipe or creek. In the wet season, this increased to 44% (86/197) of households including rainwater (Figure 3-5b). Only one family in the study primarily purchased water. In the dry season, 56% (110/197) of households used the creek for bathing (Figure 3-5c) including some residents who had water piped to their home or yard. This decreased in the wet season (Figure 3-5d).

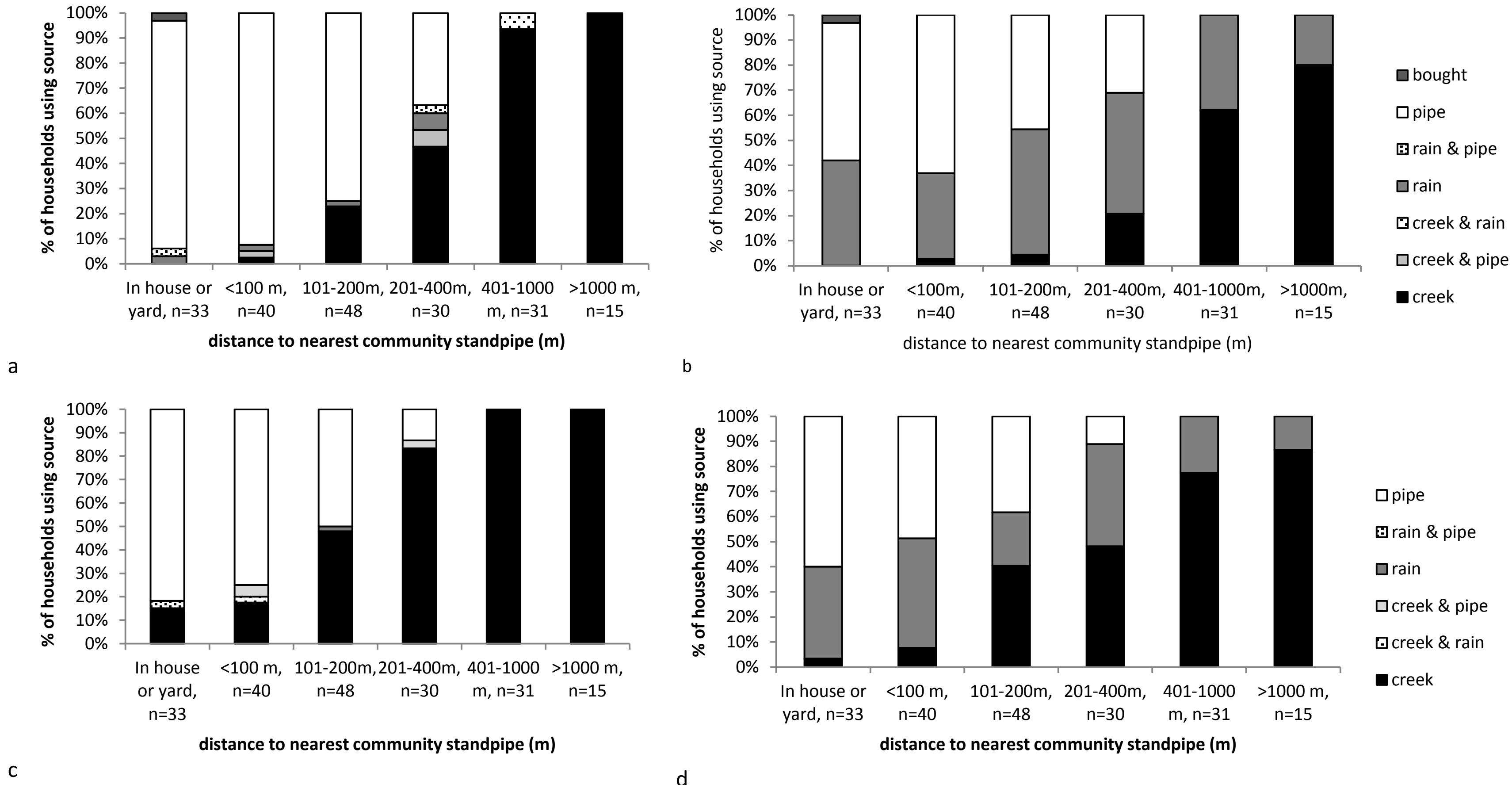

Figure 3-5 Percentage of residents using water source by distance to the nearest community standpipe. a shows dry season drinking water; b wet season drinking water; c dry season bathing water; and d wet season bathing

In an open-ended question about when the respondent would usually drink creek water, only 3% (6/198) stated that they do not. Typical responses included when at the farm, in the forest, swimming, or when bathing in the creek. Reasons given for choosing to drink creek water included convenience, but also a taste preference, with many residents finding creek water more refreshing.

Households typically stored their drinking water in a covered container (190/193, 98%). These survey responses were supported by observations of the containers during the interviews (Figure A-3). Those which served water by scooping from the container with a dish, such as a mug, rather than by pouring or using a tap, were at higher risk of diarrhoea (p=0.050) (Table 3-4).

Thirty-one respondents said that they always treat drinking water, with a further 62 treating sometimes (e.g. for a sick person). Treatment was by boiling (52%, 47/91), adding hypochlorite solution such as household bleach (38%, 35/91), both (8%, 7/91), or by straining (2%, 2/91).

Sanitation

Most households had pit latrines (146/198, 74%). Twenty percent had pour flush toilets (39/198), all of which were in the Food for the Poor housing development. The number of households without access to a toilet (2/198, 1%), using a bush toilet (defined here as a pit toilet lacking a roof and/or walls) (5/198, 3%), or who had piped flush toilets (6/198, 3%), was too small to allow for an analysis on the impacts of sanitation type (Table 3-4).

The presence of fecal matter on the toilet bowl or seat during inspection was marginally associated with diarrhoea (p=0.088) (Table 3-4).

Logistic Regression

After analysis, only five variables remained in the final binary logistic model. Extended family type, listing after eating as a time to wash hands, and serving drinking water by scooping from a container increased risk, while listing personal hygiene as being related to diarrhoeal disease and its prevention, and having water piped directly to the house or yard, decreased risk (Table 3-5).

Table 3-5 Binary logistic regression model for diarrhoea in the last 2 weeks

Variable	exp(β)	95% Confidence Interval	*p* value
Serving method: scooping	4.221	(0.885-20.132)	0.071
On-site tap (house or yard)	0.093	(0.012-0.727)	0.024
What causes diarrhoeal disease (open-ended question)?			
Poor personal hygiene (e.g. not washing hands)	0.347	(0.107-1.128)	0.079
When do you usually wash your hands? (open ended question)			
After eating	2.607	(1.064-6.391)	0.036
Household type: extended vs. other	3.670	(1.620-8.311)	0.002
Constant	0.037		0.000

The *p*-value of the Hosmer and Lemeshow test for measuring the goodness of fit for the model was 0.882. This is greater than 0.05, indicating that the results of the model were not significantly different from the observed cases. The area under the receiver operating curve (ROC) was 0.762, where 0.5 indicates no model discrimination and 1.0 indicates perfect model discrimination. Scores between 0.7 and 0.8 indicate "fair" model discrimination (Kleinbaum and Klein, 2010).

Gender and Water

Observers noted 425 water collection trips from all 16 water sources during the 32 observation days. Most collection trips were by children aged ten to 15, with males making the most trips (Figure 3-6).

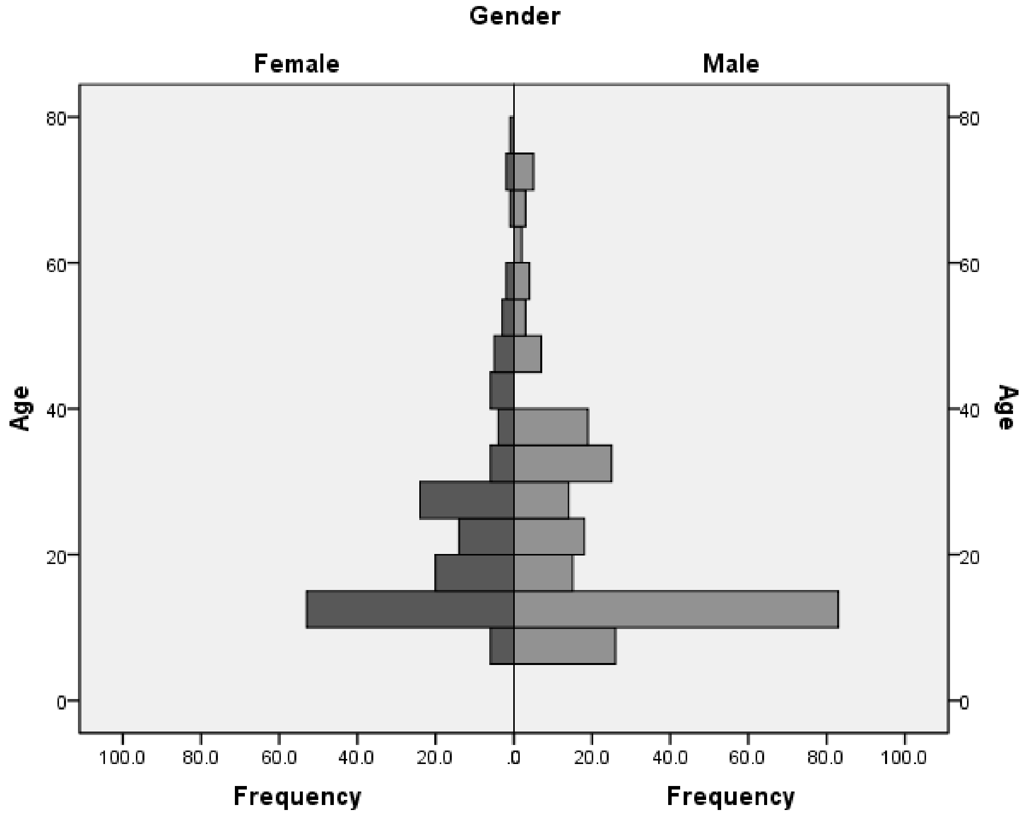

Figure 3-6 Observed water collection by age and gender

In contrast, 30 of the 42 (71%) observed incidences of someone washing clothes or washing dishes (all of which were noted at the creeks, none at standpipes) were by females.

When asked if children ever collected water in their household, 31% of households containing children (57/182) stated that children never collected water. Only 5% of households containing men (10/190) stated that men never collected water in their household, while 13% of households containing women (25/189) stated that women never collected water.

When asked which gender is primarily responsible for having safe drinking water in the home, 70% of respondents (137/196) stated that it was neither primarily a male nor a female responsibility, while 25% (49) replied that it is a female responsibility, and 5% (10) replied that it is a male responsibility.

When asked the same question regarding teaching children about hygiene, 76% (149/195) responded that it is neither primarily a male nor a female responsibility; 23% (45) replied that it is a female responsibility; and 1% (1) replied that it is a male responsibility.

3.4.3 Household water

The 198 households who participated in the water sampling portion of the study represented 965 people, or 78% of the community's total population of 1243. The average participant household size was 4.9 ($\sigma = 2.0$), with a range of one to 14.

Most household water samples (59%, 119/198) had TTC in the very high risk category, above the detection limit of 1000 cfu/100mL. This is higher than the levels found in other studies, with Clasen et al. (2003) noting 12.9% of household samples in that range and Copeland et al (2009) noting 6.1%. Only nine household samples in the present study (5%) had TTC below the detection limit of ten cfu/mL (Figure 3-7).

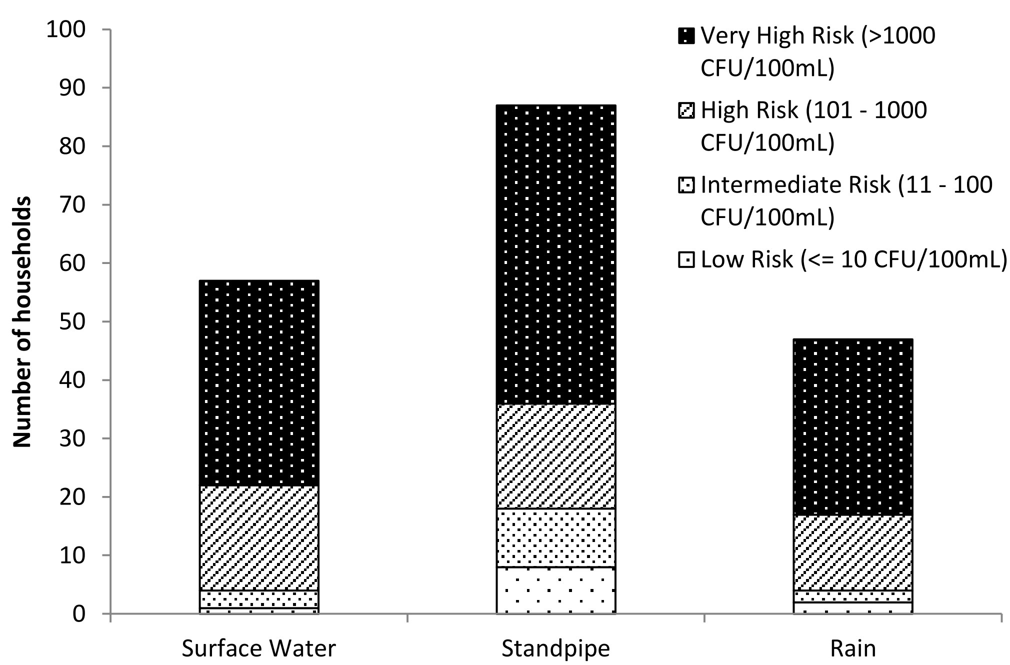

Figure 3-7 Household risk categories by source

Three households said they had added chlorine to their water, but only one had detectable chlorine in the sample provided. This sample was included in the descriptive analysis, but was removed for the statistical analysis. Another household was also removed from the statistical analysis because it had an in-line cartridge filter installed in the pipe between their large storage tank and kitchen tap. These two samples had relatively low TTC for this study (less than ten cfu/100mL and 50 cfu/100mL respectively) which may have been due to the treatment, rather than the other parameters analyzed here. One household said that their water had been strained, but it remained in the analysis, as did one household whose water had been boiled.

For just under half of the samples, the drinking water source was a standpipe (44%, 88/198). This was followed by surface sources (29%, 57/198), then rain (24%, 48/198) (Table 3-6). Several households (3%, 5/198) had water that was composed of a mix of sources (e.g. part pipe water and part rain water). These were not included in the table.

Interview bias, in which a household may claim to be using an improved source when it is actually using an unimproved source, was not a concern in this study because of the significant quality differences between sources (Levy et al., 2008; Wright et al., 2004). The primary difference was in observation of colour (surface water had a red tint), but turbidity, EC, and pH also provided measureable differences (Table 3-6). The pH of both surface and standpipe water increased from source to the served drinking water sample.

Table 3-6 Summary of household water quality parameters by source. Median with interquartile range in brackets

	Surface	Standpipe	Rain
n	57	88	48
TTC, cfu/100mL	>1000 (630->1000)	>1000 (345->1000)	>1000 (505->1000)
Turbidity, NTU	1.3 (0.9-2.0)	0.4 (0.2-0.7)	0.7 (0.6-0.9)
pH	4.0 (3.9-4.0)	5.0 (4.9-5.3)	5.5 (5.2-5.8)
EC, µS/cm	36 (34-43)	15 (14-16)	13 (10-15)
Temp, ^{0}C	28.4 (27.2-29.2)	28.2 (27.2-28.9)	27.7 (26.5-28.4)

The wealth index was taken from the first component of the principal components analysis. This component explained 30% of variance, which is within the range given by Vyas and Kumaranayake (2006). The wealth index was normally distributed though slightly left skewed, indicating that it performed better at differentiating households in the lower range of the index than the higher.

The dependent variable for the logistic regression was selected as household water TTC less than or equal to 100 cfu/100mL, corresponding to low to intermediate risk, versus greater than 100 cfu/100mL, corresponding to high to very high risk Table 3-7). There were only 24 households in the first category.

Table 3-7 Results of unadjusted and adjusted binary logistic analysis of household water where exp β <1 indicates reduced likelihood of having water of low to intermediate risk, and exp β >1 indicates improved likelihood of water of low to intermediate risk indicates the reference category for non-binary variables

		Unadjusted		**Adjusted**	
	n	**Expβ (95% CI)**	***p***	**Expβ (95% CI)**	***p***
Wealth index		1.052 (0.788-1.403)	0.733	0.778 (0.432-1.401)	0.403
Total number of people in household		0.722 (0.665-0.784)	0.000	1.178 (0.891-1.558)	0.251
Source					
Surface†	57	-	-	-	-
Standpipe	88	3.457 (1.104-10.819)	0.033	2.473 (0.608-10.065)	0.206
Rain	48	1.233 (0.291-5.218)	0.776	1.408 (0.251-7.890)	0.697
Family					
Presence of children under age 5	99	1.504 (0.677-3.344)	0.314	1.897 (0.613-5.872)	0.267
Extended Family (vs. Nuclear)	59	0.546 (0.210-1.419)	0.209	0.410 (0.124-1.354)	0.144
Ownership					
80 gallon water tank	73	2.029 (0.903-4.560)	0.083	1.654 (0.486-5.627)	0.421

Water piped to house or yard	39	3.034 (1.293-7.119)	0.008	2.154 (0.559-8.303)	0.265
Drinking Water Storage					
Store water in container in house	186	0.233 (0.061-0.884)	0.043	2.339 (0.269-20.359)	0.441
Serve by scooping	160	0.134 (0.057-0.317)	0.000	0.087 (0.026-0.288)	0.000
Sanitation type					
Bush toilet or none†	6	-	-	-	-
Shared toilet	41	1.250 (0.128-12.252)	0.848	1.309 (0.021-83.068)	0.899
Pit or pour flush toilet	144	0.720 (0.080-6.519)	0.770	6.050 (0.280-130.844)	0.251
Piped flush	7	2.000 (0.134-29.808)	0.615	3.510 (0.197-62.551)	0.393

Only three households that stored drinking water in their house did not have a lid for their container, and so it was not possible to test for this effect. All households with wide-mouthed storage vessels, such as buckets or pots, served water by scooping. As such, it was not possible to separate the effects of storage container and serving method in this study.

Three parameters remained in the final model: whether a household served water by scooping it from a container versus pouring or using a tap or spigot, whether a household had a piped connection to their yard or house, and whether there were any children under age five in the household (Table 3-8). Type of source water did not remain in the final model, nor did wealth index.

Table 3-8 Final binary logistic model, where exp β <1 indicates a reduced likelihood of having water of low to intermediate risk, and exp β >1 indicates an improved likelihood of water of low to intermediate risk

	Exp β (95% CI)	**p**
Wide mouth container, serve by scooping	0.110 (0.042-0.287)	0.000
Water piped to house or yard	3.020 (1.152-7.916)	0.025
Presence of children under age 5	3.079 (1.159-8.181)	0.024
Constant	0.329	0.014

The model had a Hosmer and Lemeshow test *p*-value of 0.107. This indicates that the model results were not significantly different from the observed results. The area under the receiver operating curve (ROC) was 0.803. This indicates "good" model discrimination (0.5 indicates no and 1.0 indicates perfect model discrimination) (Kleinbaum and Klein, 2010).

3.5 Discussion

Using an improved water source did not reduce risk of diarrhœa in this study. However, respondents were only asked to list their primary drinking water sources in the wet and dry seasons. They were not asked which types of water (i.e. rain, creek, standpipe, or purchased), members of the household had actually consumed in the previous two weeks. Periodically drinking contaminated water can eliminate the health benefits of drinking improved or treated water most of the time (Hunter et al., 2009). Only six respondents stated that they did not usually drink creek water.

On the other hand, although the unimproved creek water sources available in this community were of high risk in terms of TTC while the improved standpipe water was of low risk, the median household had drinking water of very high risk regardless of the source. Many previous studies have highlighted the issue of contamination of drinking water during transport, storage, and serving (Clasen and Bastable, 2003; Copeland et al., 2009; Wright et al., 2004). These studies have tended to show higher levels of household contamination with improved sources, but die-off of indicator organisms being prevalent in higher risk sources (Levy et al., 2008; Wright et al., 2004). In contrast, the present study found high levels of contamination for all sources. In fact, once other covariates were considered, household drinking water TTC from rain, standpipes, or surface sources were not significantly different. This result is in contrast to similar studies performed in Honduras (Trevett et al., 2004) and Ghana (McGarvey et al., 2008), suggesting that the levels of in-home contamination noted in St. Cuthbert's may be so high as to obscure the effects of all other factors.

Other risk factors related to water had the highest impact on diarrhoea in the final model for the first part of the study, both in terms of minimizing risk (having an on-site tap, exp $\beta = 0.093$) and maximizing risk (serving by scooping, exp $\beta = 4.221$). Improved access to water through an on-site tap ensures an adequate quantity for personal and domestic hygiene (Howard, 2003), as well as reducing water transport and storage. Serving drinking water by dipping cups into their water bucket, as many households did, has been found elsewhere to increase fecal bacteria in water storage containers (Pickering et al., 2010). Having a water storage container with a mouth wide enough to accommodate hands, and scooping, as opposed to using a tap or pouring, has been found elsewhere to be a significant factor in reducing drinking water quality (Clasen and Bastable, 2003; Oswald et al., 2007; Roberts et al., 2001). This may be from hands contacting the water, but also because cups themselves can be sources of contamination (Rufener et al., 2010).

Both of these factors were also significant in terms of measured household water quality. In this study, the impact of storing water in a vessel with a wide mouth and serving water by scooping was so large as to obscure nearly all other effects. Educating community members about the risks of scooping water, and improving access to better storage containers (i.e. with taps or easier pouring), should be a priority in improving drinking water quality.

Although having a pipe connection to the yard or house was related to improved water quality, it is not possible to extend the piped service directly to each household's yard or house in most developing communities. In St. Cuthbert's, as with many Amerindian villages in Guyana, the capacity of the existing system is limited; housing is of low density; and the topography within the community, including areas of thick jungle and creeks, is challenging.

These results have important policy implications. Although St. Cuthbert's had a deep well providing a low risk water source that was within one kilometre of most households in the community, the residents themselves did not have low risk drinking water. This was largely due to post-collection contamination and the selection of more convenient, but unimproved, sources. This illustrates that the provision of an improved water source by an outside agency, whether governmental or non-governmental, will not necessarily improve drinking water quality in a community in the absence of improved water hygiene practices (such as safe storage and serving methods) and when residents are not persuaded to choose the improved source over more convenient traditional sources, such as creeks. The provision of the well may have been more successful in improving drinking water quality if it had utilized a more effective community engagement strategy and been accompanied by appropriate educational campaigns.

Several households in the community had worked to improve their situation by upgrading their rainwater collection systems with elevated large storage tanks in such a way as to provide running water directly to household taps. This also eliminated the need for storing water in buckets and scooping. There were not enough rain water systems of this sort to test whether the impact is similar to being connected to the community well, but the concept is promising.

Two parameters related to hygiene knowledge remained in the final model for diarrhoeal episodes. The first was knowing that hand washing and personal hygiene prevent diarrhoeal diseases. Only 36 households were in this group. This may have affected the household's behaviour in a way that increased hand washing. However, it is also possible that people holding this belief censored their reporting of diarrhoea to prevent the enumerator from thinking of their household as having poor hygiene.

The second hygiene parameter was listing "after eating" as a time for washing hands. Effective hand washing at critical times, such as after the toilet and before eating, is known to reduce the transmission of pathogens (Curtis and Cairncross, 2003). However, questionnaire responses typically overestimate actual practice (Pinfold and Horan, 1996) and instead highlight what the respondent perceives to be good behaviour (Manun'Ebo et al., 1997). It is possible that in this study respondents who were uncertain of the correct answer erred on the side of listing too many times rather than too few. These households may have listed before eating and after using the toilet, but those who also emphasized after eating when surveyed may not have fully understood why hand washing is important for health.

Luby et al (2009) found that keeping soap at a hand washing site doubled the likelihood of hand washing with soap, but other studies have shown little agreement between proxy indicators, such as presence of soap or self-reporting, and observed hygiene practices (Biran et al., 2008; Manun'Ebo et al., 1997) or hand contamination (Pickering et al., 2010). The absence of soap at the hand washing site was not a risk factor in this study.

The hygiene portion of the survey only looked at hand washing, and did not touch on other matters of personal and domestic hygiene that could play a role in disease transmission. This study did not look at factors such as eating outside of the home, drying hands after washing, and using reusable cloths to dry dishes, which other studies have found to be significant (Al-Ghamdi et al., 2009).

St. Cuthbert's had extended sanitation coverage, with only seven households not having access to an adequate latrine or toilet. Some households shared toilets, but these were private arrangements between neighbouring households, often family, and not public toilets. Having the toilet seat (and bowl in the case of flush toilets) free from fecal matter was marginally associated with reduced diarrhoea in this study, though the variable did not remain in the final model. Not all households in the study allowed for an inspection of their toilet. It is possible that some respondents chose not to allow access because the latrine was not in a state that they wanted the enumerator to see, or from a sense of privacy. These were not random omissions and may have biased the sanitation statistical results. Some households use a "tinnie" (chamber pot) instead of their latrine at night because of snakes, feral dogs, etc. There was no question on the survey about tinnie usage, so it is unknown how widespread this practice is. Solid waste management was not included in this study, though local residents expressed their concern in the general sanitation comments portion of the questionnaire, and it has been found elsewhere to be a health risk factor (Ferrer et al., 2008).

Family type was significant in this study. This may have been because this variable represented a combination of several other factors. For example, extended families were larger on average (p=0.000) and had more members over age 50 (p=0.000). It is not clear how the presence of children under five years old in the household would relate to improved household water quality. It is possible that these households were especially diligent out of concern to protect their young children. It is also possible that these families had closer and more recent ties to the health centre due to vaccination programs and so had more recently been exposed to posters and messages about safe water and hygiene. Whatever the cause, this is a positive trend.

This study would have benefited from including alternative stakeholder engagement methods in addition to the questionnaires in order to solicit feedback from community members about their perceptions and traditional knowledge regarding diarrhoeal disease, its prevention, and WASH.

A limitation in this study was data censorship. More than half of households (59%) had TTC greater than 1000 cfu/100mL. As a result, it was not possible to use parametric statistical methods in the analysis and it was necessary to use non-parametric methods.. The logistic regression methods used are limited in that they are not able to distinguish between the households below the threshold, or likewise between the households above the threshold, and so lack sensitivity. On the other hand, 100 cfu/100mL is already high for drinking water, and the priority must be to determine the most critical parameters for dropping the risk to the median household.

3.6 Conclusions

The key findings in this study were:

- The provision of an improved water source, namely a borehole, did not ensure safe drinking water to the whole of St. Cuthbert’s. Households greater than 200m from a public standpipe were more likely to identify other water sources as their primary water drinking water source in the dry season.
- Post-collection contamination of drinking water is a significant concern in St. Cuthbert’s, regardless of the source. The actual practice of household water treatment, as determined during household water testing, is less widespread than questionnaire responses implied. Other methods and technologies, alternative to boiling and bleach, should be piloted to see if they increase treatment rates.

- Having a water connection directly to the yard or house significantly reduced the probability of a household member having had diarrhoeal disease in the previous two weeks, and the likelihood that the household's drinking water was of "high" to "very high" risk.
- Storing water in a wide-mouthed vessel, such as a bucket, and serving water by scooping from it, was the most common practice in the community but was associated both with increased rates of diarrhoeal disease and with having drinking water in the "high" to "very high" risk category.
- Diarrhoeal disease was related to hygiene knowledge in the household. Households where the representative knew that diarrhoeal disease can be connected to poor personal hygiene and not washing hands were of less risk for illness. Those that provided incorrect handwashing times as critical for preventing illness, namely after eating, were at higher risk of illness.
- Family structure is important in household risk evaluation. Extended families were more likely to have had an incident of diarrhoeal disease, while families with children less than age five were more likely to have water of only "low" to "intermediate" risk. These factors are poorly understood and should be further studied.

3.7 Acknowledgements

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3.8 Connecting text to Chapter 4

In the baseline study described in Chapter 3, St. Cuthbert's, Guyana, was found to have high rates of post-collection contamination of drinking water, and was thus a candidate for household water treatment. The following chapter addresses the first objective of the thesis, that being to test the performance, user acceptance, and sustainability of the biosand filter in a Guyanese Amerindian community as compared to other household water treatment technologies, namely ceramic candle filters and hypochlorite solution.

This chapter was prepared as a manuscript to be submitted to a peer-reviewed journal in 2013. It was co-authored by Dr. Chandra Madramootoo, who supervised the work. All literature cited in this manuscript is listed at the end of this thesis.

CHAPTER 4 Comparing adoption and sustained use of biosand filters, ceramic candle filters, and hypochlorite solution, in St. Cuthbert's, Guyana

4.1 Abstract

The efficacy of many household water treatment devices in removing coliform bacteria has been established. However, adoption and sustained use of these technologies has been low. Household factors relating to adoption are primarily studied in the context of a single technology, and few studies account for potential differences in user acceptability of different technologies. This study compared adoption and sustained use of three household water treatment technologies: biosand filter, ceramic candle filter, and hypochlorite solution, in 50 households each in the Guyanese Amerindian community of St. Cuthbert's. Households were interviewed and their water quality sampled after one month and one year to confirm treatment. Results showed that ceramic candle filters had the highest adoption (67%) and sustained usage (36%) rates, followed by hypochlorite solution (31%, 20%) and biosand filters (36%, 4%). The only significant household parameter relating to technology adoption and sustained use was the type of technology provided to the household. Other household parameters, such as drinking water source or wealth index, were not significant. Households using treatment methods had improved drinking water quality as compared to control households over the study period.

4.2 Introduction

Approximately 94% of Guyana's population has access to improved drinking water (WHO, 2010), where "improved" refers to piped water (to the home, yard, or public standpipe), boreholes, protected wells or springs, or rainwater. However, this access is limited to the coastal region. In the "hinterland" regions, where the ethnic majority group is Amerindian, only 11% of households had access to improved drinking water as of 2002 (Government of Guyana, 2007).

Improvements to environmental health infrastructure in hinterland communities are challenging due to poor accessibility and low population density.

The World Health Organization (WHO) promotes household water treatment and safe storage (HWTS) as an intermediate step towards providing safe water to households before improvements to infrastructure are possible. These households are at risk of having their drinking water contaminated at the source or during collection, transport, and storage (Clasen and Mintz, 2004). Researchers have studied the effectiveness of different HWTS technologies at reducing indicator microbes in the laboratory and field (Stauber et al., 2006), and diarrhoeal disease under controlled efficacy trials (Brown et al., 2008; du Preez et al., 2011; Fabiszewski de Aceituno et al., 2012; Tiwari et al., 2009).

However, there is a need for further study of user acceptability of HWTS (Schmidt and Cairncross, 2009a). It is unclear to what extent HWTS practices are sustained after project implementers leave a community. Regardless of its theoretical technical performance potential, any engineering design fails if it is not used by the target population (Stephenson and Peterson, 1991). The few studies in the literature which have looked at acceptability of HWTS suggest that usage rates are much lower than efficacy studies would suggest (Arnold et al., 2009; Luby et al., 2008).

For many implementers, HWTS is one component of a larger health or development program. To simplify the process, some organizations adopt a particular treatment technology or method and promote that one method across all cultural and geographical locations where the organization works. However, consumer acceptability may differ between technologies, and which technology an implementing agency selects may significantly affect project success. If a particular method is less culturally acceptable than an alternative, an organization may be using resources inefficiently by attempting to scale up a less than optimal technology. Project evaluators may then incorrectly interpret project failure as a failure of HWTS in general rather than the failure of a particular product within a particular market.

Two previous studies compared user preferences for HWTS (Albert et al., 2010; Luoto et al., 2011) in Kenya and Bangladesh respectively, but each cycled technologies through the same households at a rate of only two months per product, with a household enumerator and regular sampling visits throughout. This would not provide a clear indication of what sustained use of those technologies would be over a longer period.

Although nearly half of households in Guyana claim to practice HWTS (Rosa and Clasen, 2010), few methods are available on the market. Dilute hypochlorite solution was newly made available as a product called "Chlorosol," a joint project from the Ministry of Health, PAHO, and a local producer. As part of that project, the Ministry of Health sponsored radio and television advertisements of Chlorosol, which were running through the study period. However, the product was only available periodically. Guyana Water Inc., the national water company, was considering the promotion of biosand filters, but at the time of this study had only one pilot project underway. Ceramic candle filters were not available in Guyana at the time of this study, but are common in neighbouring Brazil.

St. Cuthbert's is an Arawak village along the Mahaica River in Guyana, South America. The community has one borehole supplying a series of intermittent public standpipes, but residents also use creek and rain water for drinking. Post-collection contamination of drinking water is widespread in households in this community (Chapter 3).

The goal of this study was to determine how making hypochlorite solution, biosand filters, or ceramic candle filters available to a household would 1) influence the likelihood of adoption and of sustained water treatment and 2) improve household drinking water quality after one month and one year of use.

4.3 Methods

For this study, adoption of a treatment was defined as the regular use of the treatment after one month. Sustained use was defined as the regular use one year after receipt.

4.3.1 Recruitment

Households were recruited for the study through posters in local shops, an announcement at the village's regular community meeting, and through door-to-door visits. Households that received a treatment were permitted to keep it after the study. Households did not receive any further financial or material remuneration for participating.

In this study, a "household" was defined as a group of people with shared drinking water storage. A single building could include multiple groups who cooked and collected water separately from one another. A household could also be made up of people living in separate buildings but who cooked together and had a common drinking water storage. Both situations occurred in this community.

To participate in the study, households were required to foresee remaining in the community for the entire one-year study period. This excluded foreign teaching volunteers and a team of short-term construction workers. The household representative needed to be at least 18 years of age.

4.3.2 Technologies

Local workers constructed the biosand filters from concrete using a Bush proof-style mold (Fewster and Mol, 2004) lent to the project by GWI (Figure A-4). Two test filters were run with local creek water before the experiment in order to estimate the necessary ripening period. Three additional test filters were run with creek water for 28 days in June and July of 2010 and sampled every third day in order to confirm that the treatment was effective with the local water. The initial test filters reduced thermotolerant coliform (TTC) colony forming units (cfu) in the water after eight and six days, the second set reduced TTC after seven days. During installation, households were instructed to dose the filter for the first nine days with surface water, without drinking the filtered water, to allow for filter ripening. These households received approximately 50 mL of Chlorosol to treat their water instead of the filter during this period. The cost of the biosand filters

(Table 4-1) did not include the cost of the steel mould. Sand was sourced locally. Some implementing agencies reduce the costs of their biosand filters by requiring recipient households to provide the required labour as partial payment rather than hiring local workers. Such an arrangement would have reduced the unit cost by up to 41% (Table 4-1).

The ceramic candle filter was composed of two 18 L buckets with three ceramic candles and a spigot (Figure A-5). Ceramic candles and spigots were imported from Cerâmica Stéfani of São Paolo, Brazil.

The Environmental Health Division of the Guyana Ministry of Health donated approximately half of the Chlorosol for this experiment. The remaining Chlorosol was purchased from a local supplier. The cost estimate (Table 4-1) assumed purchase of all of the necessary Chlorosol for one household for one year.

Because the ceramic candle filter contained a built-in 18 L storage compartment with a spigot for the treated water, households assigned to the Chlorosol and biosand filter groups received an 18 L water jar with narrow opening, lid, and tap to ensure that all treatment groups benefited equally from safe storage (Figure A-7). These containers were imported from Rotoplastics Trinidad, Inc.

Table 4-1 Costing of treatment options in $CAD. Transport included only costs related to trucking materials from Georgetown and from the central village to people's homes, where applicable.

	Total	Materials		Labour		Transport	
Treatment	**per unit**	**per unit**	**% total**	**per unit**	**% total**	**per unit**	**% total**
Chlorine	$21.80	$20.57	94%	$0.00	0%	$1.23	6%
Ceramic	$42.65	$40.18	94%	$0.00	0%	$2.46	6%
Biosand	$86.50	$44.62	52%	$35.72	41%	$4.93	6%

4.3.3 Experimental Design

The study took place from June 2009 to August 2010.

Households initially answered a survey regarding household composition, socio-economic indicators, primary wet and dry season drinking water source, and household sanitation. Volunteer names were divided into two boxes, one containing the names of those who used standpipe water as their primary drinking source during the dry season, and the other containing the names of those who used creek or rain water.

Representatives from Guyana Water Inc., PAHO, and the Ministry of Health spoke at a community meeting where they each presented information on household water treatment in general, and then particularly on biosand filters, ceramic candle filters and Chlorosol respectively. At the meeting, the guest speakers randomly selected names from the two boxes, with proportional selections from each box so that one-quarter were assigned to each study group (Figure 4-1).

Distribution of the technologies was staggered over four weeks in June 2009. Chlorosol households collected their treatment immediately after the community meeting and did not receive further training, though the opportunity was available to ask questions. Ceramic candle filter households collected their treatments one week later and received three to five minutes of one-on-one review instructions. Biosand filters were delivered to individual houses approximately three weeks later with 20 to 30 minutes of individual instruction on filter operation and maintenance while technicians installed the filters.

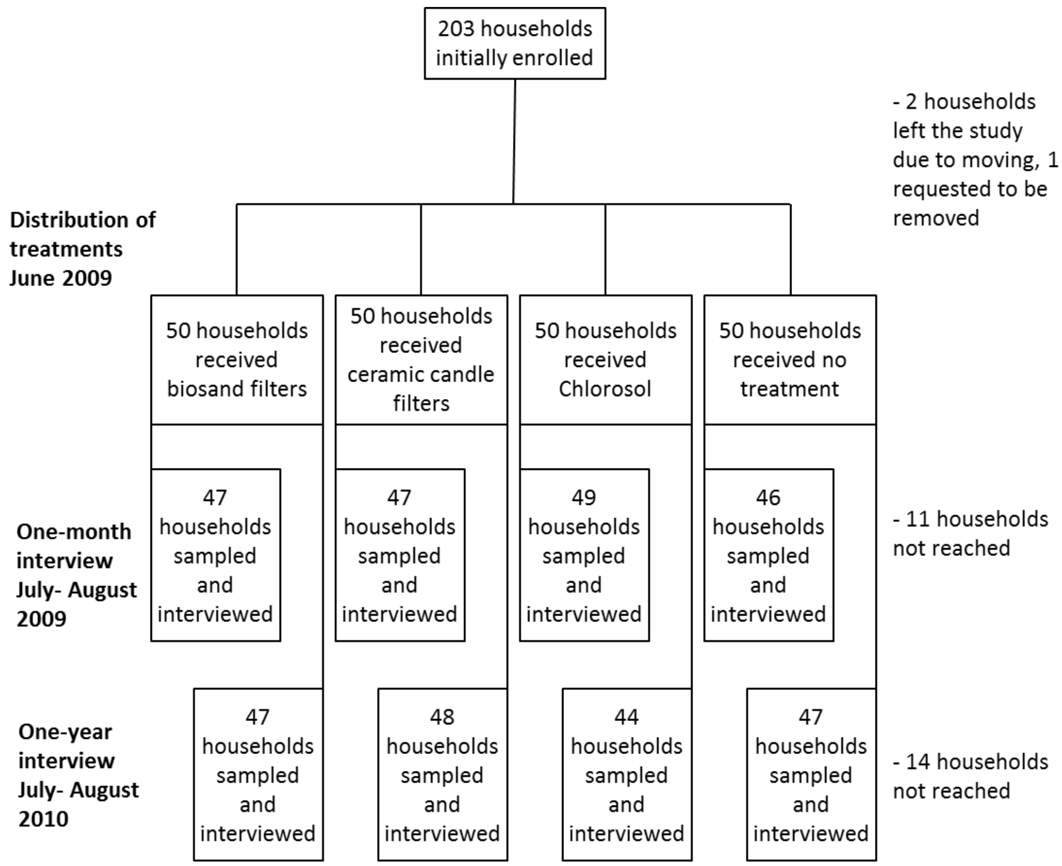

Figure 4-1 Flow chart of experimental design. Households "not reached" are those which, after multiple visits, did not have a household member available for surveying

Households in the three treatment groups were given an illustrated set of instructions demonstrating the use and maintenance of their method. Six months after the community meeting, all households in the community received a wall calendar with an illustrated reminder about safe drinking water. After nine months, a technician visited treatment households to answer questions, troubleshoot, and provide replacement Chlorosol or ceramic candles as necessary.

Households were surveyed approximately one month (July 2009) and one year (June-July 2010) after the installation of the treatments as to their continued usage and opinions on the treatment (Figure 4-1). Enumerators took water quality samples to confirm usage during both visits, with Chlorosol samples tested for free and total chlorine and filtration samples tested for electrical conductivity

(EC). Enumerators recorded observations on filters and storage containers for the presence of water to confirm usage. If no one was at home, households were re-visited several times until someone was reached, or the survey period had ended.

Households that self-reported use of the treatment were asked additional questions about their experience. The questions on these surveys were multiple-choice with responses on an ordinal scale. There were four sections. The first was a single question on overall opinion (five point scale: very good to very bad). The second was a set of four questions on sensory perception of treated water (five point scales: much better to much worse, with temperature being much colder to much warmer). The third was a question on the perceived health impact of the technology on the household (five point scale: much better health to much worse health). The forth was composed of six questions about the respondent's perceptions of the technology itself (three point scales with positive, neutral, and negative options).

During the one-year survey, all households, including those in the control group, were asked to rank the treatments and to offer comments on their opinions of all methods.

Households were not warned of enumerator visits in advance. However, they would have been aware that testing was occurring throughout the village over that time, and would have been able to see the enumerators approaching their house. As such, although courtesy bias was reduced with confirmatory water quality testing, it could not be fully eliminated.

4.3.4 Water Quality Analysis

Household representatives provided drinking water samples from a drinking cup. In households that claimed to have treated their water with chlorine, free and total chlorine were measured onsite using the N,N diethyl-p-phenylenediamine (DPD) colourimetric method (Hach Company, Loveland, CO). Turbidity was measured *in-situ* using a Lamotte 2020e handheld turbidimeter (Lamotte Company, Chesterton, MD). Temperature and electrical conductivity (EC) were also measured *in-situ* using an YSI 556 multimeter (YSI Inc., Yellow Springs, OH). Thermotolerant coliform colonies (TTC) were enumerated using the membrane filtration method (APHA et al., 1998) with a DelAgua incubator and methyl laurel sulphate broth as a medium (University of Surrey, 2004). These samples were transported in a cooler to the laboratory and tested within 6 hours. Samples containing chlorine were not neutralized with sodium thiosulphate, and so TTC levels for Chlorosol samples may be underestimated.

4.3.5 Data Analysis

PASW Statistics 18 (IBM Corp., Armonk, NY) was used for statistical analysis. Chi-squared analysis and Fisher's Exact test indicated independence of categorical factors. Kendall's tau-b test was used to determine independence of ordinal factors. T-tests and ANOVA were used to determine independence of normally distributed continuous variables.

An effect was considered to be significant at p values lower or equal to 0.05. It was considered marginal at p values less than 0.10.

A socio-economic index was developed using principal components analysis (Vyas and Kumaranayake, 2006). Seventeen survey responses and observations were used for the analysis, including ownership of: fridge or freezer, cell phone, sofa or chair with cushions, bed with mattress, motorcycle, vehicle, television, 80 gallon water tank, shop, or radio. Other variables included: access to electricity, type of roofing material (zinc versus thatch), type of housing material (concrete versus wood), primary type of stove (gas, kerosene, or wood), whether the inside of the house was painted, number of rooms, and type of sanitation (own a piped flush toilet, own a pit latrine or pour flush toilet, use neighbours latrine, or no latrine).

4.3.6 Ethics

The Minister of Amerindian Affairs of Guyana and the village leader of St. Cuthbert's were briefed and provided verbal approval before the onset of the study.

Participants signed a consent form prior to enrollment. They were informed that enrollment in the study was voluntary, and they could withdraw from the study at any time or skip any question they did not wish to answer. The study protocol, consent form, and survey tools were reviewed and approved by the Institutional Review Board in the Faculty of Medicine at McGill University (Study # A02-E01-09A).

4.4 Results

4.4.1 Enrollment and completion

The recruited households represented 979 people (79% of the estimated 1243 residents), with a mean household size of 4.8 (SD = 2.1).

4.4.2 Technology adoption and sustained use

Respondents in the ceramic filter group had the highest rate both of self-reported adoption (44/48, 92%) and of treated water at the time of the one-month survey (32/48, 67%). Chlorosol had 82% (40/49) self-reported adoption, with only 31% treated water (15/49). Biosand filters had only 57% (27/47) self-reported adoption, but a slightly higher treated water rate than Chlorosol at 38% (18/47) (Figure 4-2).

After one year, ceramic candle filters remained the most likely group to have treated water in their home, but dropped to 36%, while Chlorosol fell to 20%, and biosand filters to only 4% (2/47) (Figure 4-2).

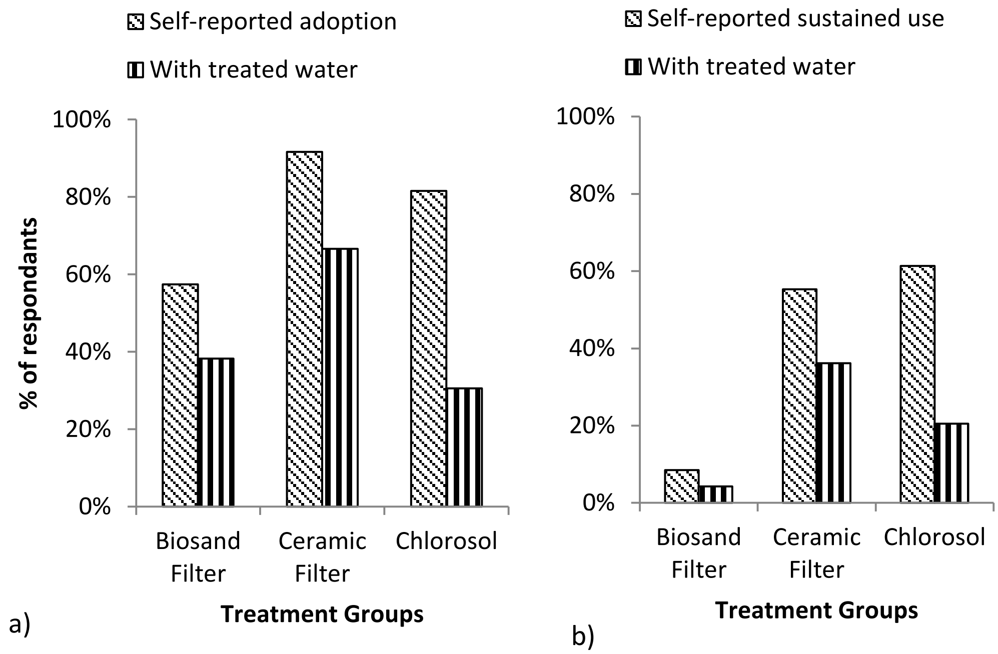

Figure 4-2 Adoption (a) and sustained usage (b) of treatments by treatment group

After the binary logistic analysis, the only significant parameter related to self-reported adoption was the type of treatment the household had received (p = 0.007). Having a shared latrine as opposed to a private one was marginally significant (p = 0.059). Treatment type retained significance when only those with treated water were considered (p = 0.006), while ownership of a kitchen tap (p = 0.027) and overall type of sanitation facility (p = 0.051) gained significance.

At the one year survey, only treatment type was significant both for self-reported users and for those with treated water at the time of the visit.

Self-reported users with treated versus non-treated water

In the one-month survey, only two parameters were different between households who had treated water at the time of visit and those who self-reported adoption but did not have treated water. The first was overall opinion of the treatment (p = 0.01), and the second was the perception that the household's health had improved because of the treatment (p = 0.02). No household factors were found to be significant.

Self-reported sustained users who had treated water were not significantly different from those who did not have treated water.

Adoption vs. Sustained usage

The households that continued to use the treatment after one year had only one significant difference in their responses on the one-month questionnaire as compared to those who stopped treatment. That was their impression of the positive impact of treated water on the family's health ($p = 0.043$ for self-reported users, $p = 0.050$ for those with treated water at time of visit). There was a marginal relationship with abandoning the treatment and finding treated water warmer (p=0.077), and having a better appearance (p=0.081). Neither marginal parameter retained significance, however, when looking only at households who had treated water at the one-year visit. For these households there was a marginal relationship with having said that the treatment was "fast enough" during the one-month survey (p=0.058).

Perceptions

In the one-month survey, several differences arose in the rating of the treatments by respondents. Self-reported adopters in the biosand group were more likely to rate their treated water as being cooler than untreated water ($p < 0.001$). The biosand filter respondents were also more likely to rate their treatment as taking up too much space ($p = 0.01$) and as being ugly ($p = 0.02$). When only households who had treated water at the time of the visit were considered, an additional difference was noted, that being that biosand filter respondents were more likely to rate their treated water as having a worse appearance than the untreated water ($p = 0.01$). There were no significant differences in perception between ceramic filter and Chlorosol households at the one-month survey.

In the one-year survey, differences were noted in the perceptions of respondents in the ceramic filter and Chlorosol groups. Self-reported users in the ceramic filter group were more likely to give their treatment a higher rating in terms of overall opinion ($p = 0.033$) while Chlorosol users were more likely to give their treated water a lower rating in terms of taste ($p = 0.044$). However, neither of these perceptions was significant when only the subset of households with treated water were compared. As with the one-month survey, the biosand filter was more likely to be rated as taking up too much space (p = 0.002) and being ugly (p = 0.002). These parameters retained significance when only households with treated water were compared (p = 0.003 and p = 0.000 respectively).

Biosand Filter

Of the 19 biosand filter adopters, three used the water for both cooking and drinking; the remainder used the treated water only for drinking. Households treated water from daily to every seven days, with a median of every two days. Adopters of the biosand filter found that the treated water was “a little colder”, and believed that their family’s health had improved. The key reasons given for not adopting the Biosand filter were that they didn’t see a need for it (6/19) and that it was too much work (2/19) (Table 4-2).

There were only two households still using the treatment at the one-year visit. Of the two, one used the water for cooking and drinking, the other just for drinking. Both households treated water every two to three days.

A common experience for households that had adopted the filter but later abandoned it was that at some point in the previous year they had left home for an extended period and when they returned the filter had dried. Ant infestations were common in these dried filters. Several households attempted to restart their filters, but were unable to due to air binding.

None of the household parameters included in the study related significantly to adoption or sustained use of the biosand filter.

Ceramic filter

Of the 32 ceramic filter adopters, only two households used the water for both cooking and drinking at the one-month survey. The remainder used the water only for drinking. The median household treated its water daily, with a range of one to two days. The key reason given for not adopting the ceramic filter was that it had broken (2/4) (Table 4-2).

At the one-year visit, one of the remaining 17 households used the treated water for cooking and drinking, while 16 used it only for drinking. Households treated their water a median of every three days, with a range of one to seven.

Drinking water source was significantly related to both treatment adoption and sustained use. Users of pipe water were more likely to adopt the treatment (p = 0.037), but less likely to sustain usage (p = 0.047).

Chlorosol

Of the 15 Chlorosol adopters, three used the treated water for cooking and drinking, while the remaining used the water only for drinking. The median time between treatments was 3.5 days, with a range of one to fourteen. Non-adopters of Chlorosol did not like the taste (3/9) or did not see a need for treatment (2/9) (Table 4-2).

At the one-year point, the nine sustained users all used the treated water only for drinking, with the median time between treatments of 3.8 days, ranging from two to seven days.

As with the biosand filter, none of the household parameters related significantly to adoption or sustained usage.

Table 4-2 Comparing expressed reasons for non-adoption among treatment groups, n = number of responses

Reasons for Non-Adoption	Biosand Filter (n = 19)	Ceramic Filter (n = 4)	Chlorosol (n = 9)
Broken/ran out	1	2	2
Haven't been home much/intend to start	4	1	1
Don't like the taste	0	1	3
Don't see a need for it	6	0	2
Too much work	2	0	0
Had a bad reaction	1	0	0
Don't like it/no reason given	5	0	1

4.4.3 Water quality

The purpose of this study was not to determine whether the technologies functioned in a household setting. The purpose was instead to investigate whether the water that the household was actually drinking had improved, controlling for seasonal differences and increased education and awareness of water issues in the community over this period. The data were censored, meaning that TTC cfu were limited to values between 10 and 1000. TTC differences between the baseline and survey water samples in treatment and control groups were analyzed using the sign rank test. Households with water treated by the ceramic filter had improved water at both the one-month and one-year samples (p = 0.000, p = 0.003), as did households which treated their water with Chlorosol (p = 0.000, p = 0.000). The significance for households with treated water from the biosand filter as compared to control households was marginal at one-month (p = 0.076). It could not be calculated at the one-year time point due to too few samples.

Temperature did not vary between treatments. EC was higher among filtered samples. Biosand filter water had higher turbidity (Table 4-3).

Table 4-3 Water Quality Parameters, (standard deviation in brackets)

Treatment	Turbidity (NTU)	Temperature (°C)	EC (mS/cm^3)	Median TTC (CFU/100mL)
Biosand	3.0 (2.2)	27.7 (2.2)	79 (37)	825
Ceramic	0.1 (0.4)	27.8 (1.3)	120 (36)	10
Chlorosol	0.6 (1.2)	27.1 (1.2)	22 (13)	<10
Control	0.7 (1.0)	27.8 (4.7)	16 (6)	>1000

Overall Ranking

All households, including those in the control group, were asked to rank the treatments. The responses were analyzed against household parameters for the first and last ranked treatments, and how each of the four options (with the fourth option being “no treatment”) ranked. The ceramic filter ranked highest overall, though its preference over the Chlorosol group did not reach significance (p =

0.255). Both ranked significantly higher than the biosand filter, which ranked significantly higher than having no treatment (Figure 4-3).

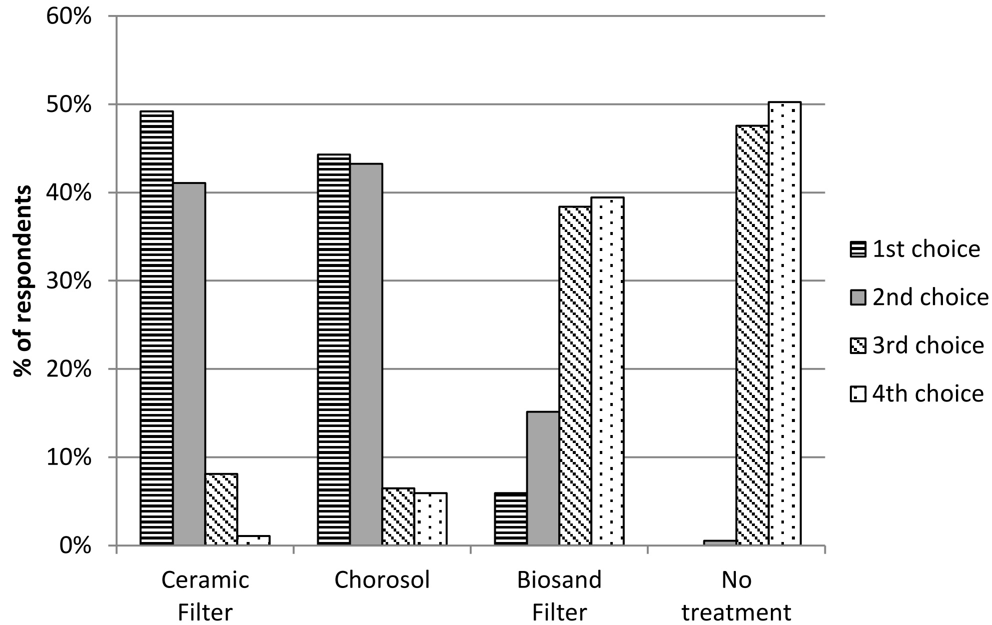

Figure 4-3 Treatment rankings

The only significant factor influencing treatment ranking was the treatment group of the respondent, with those in the Chlorosol and ceramic filter groups each more likely to rank their own treatment as first. There was no relationship between ranking of the treatments and the other household variables tested. However, when looking only at the responses from the control group, who had not received any treatments to test, the median age of those selecting Chlorosol, 45, was higher than those selecting ceramic filters, 34 (p=0.037).

Closing interview treatment perceptions

Nearly all comments regarding the ceramic filter were positive (Table 4-4). The one respondent who liked it because he had used it before said it had been while working for international mining companies in the interior of Guyana.

Although the majority of Chlorosol comments were also positive, there were more people who gave negative feedback than with ceramic filters, primarily about the taste and odour of the treated water. The comment regarding the jars becoming “slimy” appears to have been due to algal growth. The jars were made of a white translucent plastic which would have allowed enough light to pass through for algae to grow.

The biosand filter elicited fewer positive remarks. The criticisms about the filter being difficult to use were primarily referencing how difficult it was to lift a heavy bucket high enough to pour into the filter reservoir. Some people had stopped using the filter after injuring their backs with the heavy lifting. Others referred to the need to add water every day, or that the filter dried out and became useless if it wasn’t used for a while. Of the 33 who said that they didn’t trust the filter, 12 elaborated further by objecting to “drinking the sand”, or even bringing sand into the house, and strongly believed that pouring the water “through the earth” added germs.

Table 4-4 Final comments and opinions regarding treatments

Ceramic Filter	
Pros	Easy to use and "handy" (59)
	Easy to clean (19)
	Easy to move (11)
	Just like how it works (7)
	Has a cover (5)
	Makes water safe (5)
	Good taste, clear water (4)
	No expenses, don't need to buy anything for it (2)
	Looks nice (2)
	Familiar with it, have used before (1)
	Easy for children to use (1)
	Makes water cool (1)
Cons	Very fragile (4)
	Tastes bad (2)
	Don't understand how it works, seems complicated (3)
	Bucket cover not secure, children can “trouble” it (3)
	Slow (1)
Chlorosol	
Pros	Easy and convenient (33)
	Like the jar with the tap and lid (26)
	Healthy and safe (18)
	Good taste (2)
	Not easily broken (1)
Cons	Gives water a bad smell and taste (12)
	Difficult to clean the jar, becomes slimy (4)
	Needs to be empty before you can treat again (2)
	Chlorosol gets used up, always need to get more (1)
	Don't like drinking chemicals (1)
	Difficult to remember (1)

Biosand filter	
Pros	Good to filter, makes good water (10)
	Easy to use (3)
	Makes water colder (2)
Cons	Too big and heavy (67)
	Don't trust it (33)
	Too difficult to use (28)
	Saw others didn't like it (11)
	Slow (7)
	Bad taste (6)
	Breeds mosquitos, attracts ants (2)
	Primitive (2)

4.4.4 Biosand test filters

The first two test filters, run in May and June of 2009, were run for the purpose of determining the length of time the filter required until filter effluent had lower TTC cfu's as compared to the influent water sample. One filter was run for 18 days, the second for only 12 days. The first was sampled daily; the second was sampled daily from days 1 to 7, and then supplemented with a sample on day 12. Influent was from the previous day, to account for the one day residence period.

The second set of filters was run to investigate the possibility that the biosand filter was not an effective technology for the water quality in the community, after the results of the one-month household water testing. Three filters were run in parallel for 28 days, and sampled every third day after day seven. Control samples were also taken, in which a portion of influent water was kept in a sterile container, covered in black plastic, and kept next to the filters to maintain a similar temperature. The control samples were tested at the same time as the corresponding filter effluent samples. None of the three filters exhibited improved performance after day seven, indicating that they were already ripened by this point.

Part of the high standard deviation exhibited by these filters (Table 4-5) may have been due to high variability in the creek water quality, with TTC concentrations ranging from 50 cfus to 15700 cfus per 100 mL over the study period. Higher influent concentrations were associated with higher removal rates in the filters. Although all three 2010 filters were prepared, installed, and operated as similarly as possible, were located together, and received the same influent water, filter 3 underperformed compared to the other 2. It was observed that the outlet pipe of filter 3 had been colonized by spiders.

Table 4-5 Biosand test filter performance

Sample Source	mean $\log_{10}$ TTC removal (± standard deviation)
2009 Filter 1 (days 9 through 18)	0.54 ± 0.46
2009 Filter 2 (days 7 & 12)	1.16 & 0.57
2010 Filter 1 (days 7 to 28)	1.2 ± 0.7
2010 Filter 2 (days 7 to 28)	1.5 ± 1.4
2010 Filter 3 (days 7 to 28)	0.4 ± 0.3
2010 Control samples (days 7 to 28)	0.1 ± 0.2

4.5 Discussion

The most significant factor in determining whether a household had treated drinking water at the time of the follow-up visit was which technology they had received.

Unlike in previous studies (Brown et al., 2009), no relationship was found between HWTS adoption and sustained use with household water, sanitation, and hygiene indicators, source water, or other indicators such as household wealth. It is possible that the low number of households sustaining use of their treatment in this study reduced the power of this statistical analysis, or the parameters noted by Brown et al. (2009) were specific to their study area of rural Cambodia and not transferable to another community.

Believing that the treatment had improved their family's health was significant in motivating a household that had adopted the treatment to continue using it. This emphasizes the importance of educating users as to the health benefits of treating drinking water.

Albert et al. (2010) cycled hypochlorite solution, ceramic candle filters, and a flocculent-disinfectant product for two month intervals over 400 households in Kenya. They found self-reported usage of 76% for the hypochlorite solution and 73% for the ceramic candle filter. The present study reversed the ranks of the ceramic filter (92%) and hypochlorite solution (82%) at the four week follow up visit. The Kenyan study used the absence of *E. coli* in sampled water as a confirmation of treatment usage, with 51% of hypochlorite households and 39% of ceramic candle filter households meeting the requirement of <1 CFU/100mL (Albert et al., 2010). However, operating conditions play a large role in the effectiveness of treatment technologies (Baumgartner et al., 2007). This study found many households had used their technology but still had indicator bacteria in their treated water due to issues with maintenance (e.g. loose candles in the ceramic filter), improper use (e.g. insufficient chlorine dose), or post treatment contamination (e.g. contaminated storage container or cup). This was corrected by confirming treatment based on other objective measures, such as the presence/absence of total chlorine with the Chlorosol treatment, or electrical conductivity in the case of the filters.

Public health interventions fail in their purpose if target recipients choose not to use the technologies. On the other hand, a popular technology is ineffective if it does not perform. As such, it was also important to confirm that the technologies improved the quality of drinking water in the home. This study did not look at the quality of water directly after treatment, but rather at the quality of the household's water at the time of drinking. This would have allowed for possibilities of contamination during storage and serving of water, but more accurately reflects the safety of the household's drinking water. The Chlorosol product performed well with the selected indicator bacteria, as would be expected with a product that maintains a residual disinfectant for some time after treatment, and for which treatment and storage occurred in the same container. The ceramic candle filters also performed well.

The drinking water quality in the biosand filter households was only marginally better than that observed in control households over the same period. There are several possible reasons for this. One possibility would be that the biosand filter was not appropriate for the water in this community, which had low turbidity, very low pH, and high colour. However, the test filters did function with the community's water (Table 4-5), although with highly variable performance. Another possible cause is that, unlike the other two technologies, treatment was separate from storage. This introduces opportunities for post-treatment recontamination. An additional issue is that households were dosing the filters less often than recommended, with a range of daily to only every seven days. This may have affected performance. No studies in the literature to date have looked at the impact of extended residence periods on biosand filter performance. There were also limitations regarding the microbial indicator in this study. It is known that some bacteria inhabit and multiply in biologically active filters (Amburgey et al., 2005). High TTC levels may not have reflected the filter’s ability to remove actual pathogens, but rather have indicated that some (non-pathogenic) members of the coliform group are able to inhabit these types of filters. Alternative indicators, such as *Escherichia coli,* should be used in future studies in the tropics and involving biosand filters.

Of the survey questions asked to self-reported adopters of treatments, the biosand filter rated differently from the others in terms of water temperature, and perceptions of the technology being ugly and too large. As the biosand filter had the lowest self-reported adoption rate, it seems that the advantage of cooler water was not a strong motivating value, or at least not as strong as the de-motivating effect of the size and appearance of the device. It is interesting to note that six of the 47 surveyed biosand filter households did not adopt it because they did not see a need for it, compared to none in the ceramic filter group. Previous studies on adoption and sustained use of biosand filters have mixed results. A follow-up study in Haiti of 199 households one year after implementation showed 77% continued use (Fiore et al., 2010). However, this study made use of a convenience sample, in which a local driver and translator selected households with biosand filters from memory, with additional households identified by questioning community members. In both cases, households which had adopted the filter may have been more easily remembered as having a filter as opposed to households where the filter had been discarded. A study in Nicaragua following up with a 34 household group had 30% continued usage after 8 years, while another group of 200 households had only 7% continued usage after three years (Vanderzwaag et al., 2009). As with the present case, these three studies all involved filter distributions with no cost and did not require recipients to assist with construction. Continued usage of HWTS technologies requiring a contribution from recipients tend to be higher (Brown et al., 2009). This study had a self-reported sustained usage rate of 9%, which compares with the Nicaraguan study, though the present study was only one year long. However, this is the first biosand filter adoption and usage study known in a South American Amerindian community, who may have particular cultural values and practices that are less amenable to this particular technology.

Cost also plays a role in technology selection. For each household that had improved water after one year in the Chlorosol group, five households needed to be subsidized. With the ceramic candle group the ratio was closer to one in three. However, as indicated in Table 4-1, Chlorosol was the least expensive treatment over a one year span by a considerable margin. The cost difference between Chlorosol and ceramic candle filters was large enough that subsidizing five Chlorosol households was cheaper than subsidizing three ceramic candle filter households. This cost difference must be considered.

Chlorosol is also locally produced, while no supply chain presently exists for ceramic candles in Guyana. This study did not look at users' willingness to pay for treatment, which would also influence selection.

These results provide important implications for government and non-governmental agencies concerned with household drinking water programs. All three technologies have been successfully implemented in other communities and are considered among the most promising HWTS technologies on the market. However, local conditions affected both the technical performance and the acceptance of the technologies. An improved initial stakeholder engagement process may have helped identify some of these conditions early in the project. For project implementers, early stakeholder engagement and pilot testing of technologies would lead to more appropriate technology selection.

4.6 Conclusions

A HWTS project is only successful if the community sustains use of the technologies after the implementing agencies have left. This research found that the key factor relating to sustained water treatment in households was the type of technology the household had received.

Ceramic candle filters are a promising household water treatment option in this setting. Adoption and sustained use of the treatment method were higher than that of biosand filters and hypochlorite solution. Households using the technology had significantly improved microbiological drinking water quality (from a median of >1000 to a median of 10 TTC cfu/100mL) after one month and one year of use.

Further research is recommended into the impacts of non-optimal operation of the biosand filter, especially in terms of extended residence periods.

The selection of an appropriate HWTS technology for a particular community is critical to the project's success or failure. Adoption and sustained usage rates in studies do not represent acceptance of HWTS in general, but only acceptance of the particular product. However, care must be taken in interpreting the stated preferences of a target market, as these do not necessarily correspond to actual adoption and sustained usage rates.

4.7 Acknowledgements

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The project had two local partners: Guyana Water Inc. (GWI) and the Hydrometeorological Division of the Ministry of Agriculture (HydroMet) in Guyana. Savitri Jettoo and Bhaleka Seullal of these organizations provided logistical and administrative support for the project. In addition, GWI provided the steel mold for construction of the biosand filters, while HydroMet provided the use of the YSI 556. The village council of St. Cuthbert's provided accommodation, use of the village boat for transportation, and logistical support for the duration of the study. The Guyanese Ministry of Health provided supplemental Chlorosol to the study.

Lauren Intven of McGill University assisted with the one month surveys and technology installation.

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4.8 Connecting text to chapter 5

In chapter 4, several concerns regarding biosand filters were found in the pilot study in St. Cuthbert's, Guyana. Many issues that arose may also be relevant to other communities, and it is beneficial to investigate the impacts of particular practices, namely extended residence periods, and possible steps toward the mitigation of particular problems identified, such as by reducing the height of the filter.

This chapter was prepared as a manuscript to be submitted to a peer-reviewed journal in 2013. It was co-authored by Dr. Chandra Madramootoo, who supervised the work. All literature cited in this manuscript is listed at the end of this thesis.

CHAPTER 5 Intermittent versus continuous operation of biosand filters

5.1 Abstract

Biosand filters are gravity-fed, point-of-use filtration systems for use in households without access to a continuous piped supply of treated water. The initial filter design was based on conventional slow sand filtration, but with modifications to allow for intermittent operation. Earlier studies in slow sand filtration had found that operating filters intermittently caused reductions in filter effectiveness. Continuous versus intermittent operation of these modified filters has never been compared. This study examines continuous versus intermittent operation of the biosand filter.

Eight laboratory-scale filter columns were constructed to represent field biosand filters. Five filters were operated intermittently, with dosing equivalent to one pore volume applied per day in one application, while the remaining three were dosed continuously, with one pore volume pumped per 24 hours.

Continuous operation of the filters resulted in significantly better performance in terms of removal of *E. coli* (3.7 $\log_{10}$ versus 1.7 $\log_{10}$), bacteriophage MS2 (2.3 $\log_{10}$ versus 0.9 $\log_{10}$), and turbidity (96% versus 87%). For continuous filters, *E. coli* removal and DO consumption primarily occurred before 5 cm of media depth, while MS2 removal occurred through the full 55 cm media depth, but with a declining impact of greater depths. In intermittent filters, the relationship was more complex. A large proportion of *E. coli* removal occurred after filtering through the first 10 cm of media, but further removal occurred throughout the filter depth during the residence time, up to 20 hours. For MS2, the majority of removal occurred during the residence period within the filter depth following a linear trend with time, suggesting that further improvements may have been possible with increased residence time.

This research confirms that, although biosand filters were developed for intermittent operation, the filters still perform significantly better when operated continuously. However, despite the reduction in effectiveness observed from intermittent operation, the filters still resulted in a significant reduction of microbial indicators through both operational modes.

5.2 Introduction

The World Health Organization recommends that point-of-use water treatment methods be used by households which are not yet serviced by continuously piped, treated water (WHO, 2012). Of the point-of-use treatment methods presently available, biosand filters (BSF) are considered to be one of the most promising (Sobsey et al., 2008). Key advantages to BSF are that once installed they have no recurring costs, as maintenance can be done within the household; they can be constructed with local materials by local skilled tradespeople; and they can handle turbid surface influent waters (Jenkins et al., 2011; Tiwari et al., 2009).

A BSF is composed of a concrete or molded plastic filter box housing a granular media bed of 40 to 55 cm depth above a gravel underdrain. The outlet pipe or tube, which collects water below the filter underdrain, is extended either within the wall of the filter box, or along the exterior, to a height of approximately 5 cm above the media surface. This hydrostatically ensures that the media bed remains saturated and that a protective standing head remains over the media surface at all times. A diffuser plate installed approximately 2 cm above the standing head also protects the media surface. The driving force to operate the filter is gravity. Users periodically fill the reservoir above the media surface with influent water, creating a pressure gradient between the media surface and the outlet. Flow declines to zero over time as the pressure differential decreases (Elliott et al., 2006). The time between one dose and the following is referred to as the residence period (Jenkins et al., 2011). Residence periods of 1 to 48 hours are recommended (CAWST, 2009). Filters require a period ranging from days to weeks in order to “ripen”, during which time they develop a schmutzdecke, or filter cake, and improve in effectiveness (Elliott et al., 2006). Filters are maintained by manually disturbing the first centimeter of media to suspend accumulated material, and then removing this material by decanting the standing head.

Randomized controlled trials using BSF have demonstrated significant reductions of diarrhoeal disease in vulnerable populations (Aiken et al., 2011; Fabiszewski de Aceituno et al., 2012; Stauber et al., 2012a; Stauber et al., 2009; Stauber et al., 2012b). Laboratory trials have demonstrated average microbial indicator removal rates of 1.9 $\log_{10}$ for *Escherichia coli* B, 0.5 $\log_{10}$ for bacteriophages MS2 and PRD1, 2.1 $\log_{10}$ for echovirus 12 (Elliott et al., 2008), >5 $\log_{10}$ for Giardia lamblia cysts, and 3.7 $\log_{10}$ for Cryptosporidium oocysts (Palmateer et al., 1999).

High variability and lower removal rates have been noted in field settings (Fiore et al., 2010; Jenkins et al., 2009; Stauber et al., 2006). Recent research has focussed on improving filter performance through modifications to filter operation (Kennedy et al., 2012) or modifying media (Ahammed and Davra, 2011; Ghebremichael et al., 2012). However, there is little understanding at present as to how BSF works.

In the literature, BSF are described as small scale slow sand filters (SSF) which are operated intermittently (Fabiszewski de Aceituno et al., 2012; Jenkins et al., 2011; Kubare and Haarhoff, 2010; Ngai et al., 2007). SSF is a proven water treatment method that has been used with success for the last two centuries (Crittenden et al., 2005). Historically there have been strong recommendations discouraging intermittent operation, as it has been noted to decrease filter effectiveness (Huisman and Wood, 1974; Paramasivam et al., 1980). The BSF was developed in the 1990s based on the theory that ensuring that the filter schmutzdecke remains undisturbed, wet, and aerobic would result in similar performance in intermittently and continuously operated filters (Buzanis, 1995). The reduced standing head of 5 cm in BSF as compared to 100 to 150 cm in conventional SSF (Huisman and Wood, 1974) is intended to ensure aerobic conditions be maintained in the schmutzdecke. A diffuser plate was added to protect the schmutzdecke during dosing. Other differences, such as the reduced media depth of 0.4 to 0.55 m in BSF as compared to 0.6 to 1.2 m in a conventional SSF, make the filter practical for household use.

However, literature removal rates of microbial indicators in BSF are not as high as rates published for SSF (Stauber et al., 2006). It is not clear whether these performance differences are due to the intermittent operation of the filters, or if they are due to the structural modifications in BSFs as compared to SSFs, such as the reduced media depth and standing head. No studies in the literature have directly compared intermittent versus continuous operation of a BSF.

This study compares the removal of bacterial and viral indicators (namely *E. coli* and MS2 bacteriophage) by intermittent and continuous operation of BSF using the same filter design, filter media, and influent water.

5.3 Materials and Methods

5.3.1 Column design

The columns for this experiment were designed to replicate the vertical dimensions of the CAWST V10 filter (CAWST, 2012). This particular model was selected as it already accommodates the filter modification recommended by Elliot et al (2011) of increased media depth and reduced reservoir volume. The columns were constructed of 10 cm diameter transparent acrylic tubing.

DO sensors, piezometer tubes, and sampling points were installed at locations corresponding to 1 cm above the sand surface, and 5, 10, 30, and 55 cm below, as illustrated in Figure 5-1. The diffuser plate was installed 2 cm above the standing head. Field BSF have opaque walls of concrete or plastic and so the columns were covered in black plastic throughout the experiment in between dosing or measurements in order to prevent any algal growth which would not occur in a field filter.

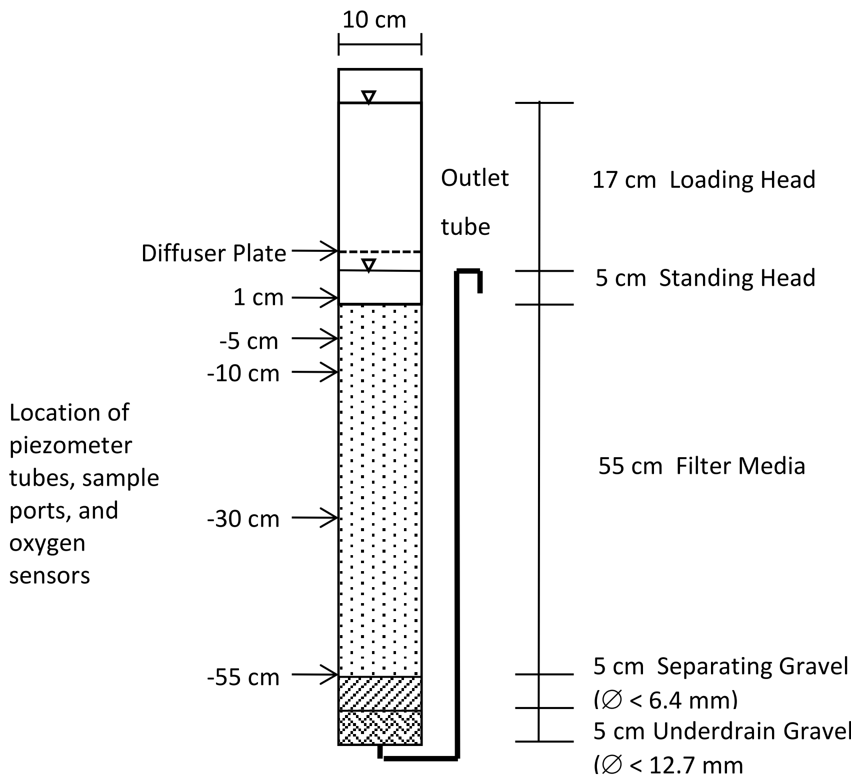

Figure 5-1 Schematic of laboratory columns

The filter media was locally purchased sand. The media had a porosity of 0.42, maximum diameter of 0.7 mm, effective diameter (d_{10}) of 0.17 mm, and a uniformity coefficient (UC) of 2.06. This is within the guidelines of a d_{10} between 0.15 and 0.20 mm, and a UC between 1.5 and 2,5 (CAWST, 2009).

The two underdrain layers were composed of locally purchased crushed gravel that was washed and sieved so that the fine top layer had a diameter range of 0.7 to 6.4 mm and the coarse bottom layer of 6.4 to 12.7 mm.

The columns were partially filled with water before adding the underdrain gravel and filter media in order to prevent air binding. As air bubbles would be a particular problem for the piezometer tubes in these columns, the distilled water used in this experiment was first boiled to decrease the saturation point of air in water and so allow much of the air to be released. It was then cooled and slowly introduced through the outlet tube in order to prevent the introduction of air through splashing or turbulence.

The dosing volume of 2.0 L was set to be equivalent to the pore volume of the filter sand and underdrain gravel. The total volume of water remaining in the filter during the residence period including the standing head, sand pore volume, underdrain pore volume, and outlet tube, was approximately 2.5 L.

5.3.2 Influent water

Water was collected daily from Lac St Louis, Quebec. It was transported to the laboratory, where it was stored overnight to reach the laboratory temperature (approximately 20°C).

Water was supplemented with *E. coli B* (ATCC# 11303) and MS2 bacteriophage (ATCC # 15597-B1) before dosing. Overnight cultures of *E. coli* were grown weekly in tryptic soy broth, divided into daily aliquots, and refrigerated at 4°C until use. MS2 was propagated in trypticase soy broth using *E. coli* C3000 (ATCC # 15597) as a host. The stock was diluted ten-fold in phosphate buffered saline (Elliott et al., 2011). Stock was divided into daily aliquots for the full experiment, then stored at -20°C until the day of use.

5.3.3 Measurements and sampling

Filter effluent samples were well-mixed. These samples were taken one to two hours after dosing, when filtration was typically 80% to 100% complete.

Influent samples were collected the day before effluent samples. They were analyzed immediately for temperature, DO, EC, pH, and turbidity. Samples for *E. coli* and MS2 were stored refrigerated overnight and processed with the corresponding effluent samples.

Control samples were collected by taking approximately 500 mL of influent water in a sterile, loosely-capped, glass media bottle, covering the bottle in black plastic, and then placing it beside the filters at room temperature until testing with the corresponding filter effluent.

E. coli was enumerated using the membrane filtration method (APHA et al., 1998) with m-coliblue24® as the broth (Hach Company, Loveland, CO). MS2 was enumerated using the double layer agar method (USEPA, 2001) with *E. coli* F_{amp} (ATCC# 700891) as a host, and antibiotics streptomycin and ampicillin to restrict growth of other microbes in the sample water.

Temperature, pH, EC, and DO were measured using a YSI 556 multi-parameter probe (YSI Inc., Yellow Springs, OH). A Lamotte 2020e turbidimeter (Lamotte Company, Chesterton, MD) was used to measure turbidity.

Nitrogen (N) as ammonia, nitrate, and nitrite were measured with Hach methods TNT 830, TNT 835, and 8507 respectively, using a DR-2800 Spectrophotometer (Hach Company, Loveland, CO). Total nitrogen samples were acidified with hydrochloric acid and stored at 4°C until the end of the experiment and measured using the perchlorate method (APHA et al., 1998)

In-situ DO measurements were taken using RedEye® oxygen patches read with a Neofox fluorescence probe (Ocean Optics, Dunedin, FL). Patches were calibrated before media placement by filling the column with distilled water then bubbling with nitrogen gas until the YSI 556 probe confirmed that 0 mg/L of oxygen had been achieved.

Readings were taken from the piezometer tubes in order to calculate instantaneous flow rates, q, and hydraulic conductivities, K. A timer was started when the loading head was at its maximum height. When readings from the top piezometer tube, which was located above the media surface (Figure 5-1), fell to predetermined levels, generally at one centimeter increments, the time was recorded as well as the readings of the other four piezometer tubes.

To calculate q, the readings from the top piezometer tube were plotted against time. A curve was fit to describe the relationship. The derivative of this curve provided the equation for flow rate for a given time. The maximum *q* occurred when the loading head was at a maximum, at a time of zero seconds.

Hydraulic conductivity, K, was calculated according to Darcy's law:

$$q = K \frac{\Delta h}{L} \tag{5-1}$$

where,

Δh was the difference in readings between two piezometers, and

L was the distance between the two piezometers.

Both q and $\Delta h/L$ were calculated and plotted against one another. The slope of the resulting line was K.

Depth samples from three intermittent filters were taken on day 60 from sample ports in the filters (Figure 5-1) at 4, 8, 20, and 24 hours after dosing, and then from effluent grab samples corresponding to water which had spent the residence period at that location within the filter. Samples were also taken from continuous filters, but only at a single time step and with a composite effluent sample.

5.3.4 Experimental design and statistical analysis

The experiment comparing continuous and intermittent operation was an unbalanced incomplete block design. Eight columns were operated in parallel, of which five were operated intermittently and three were operated continuously. The extra intermittent columns were in order to improve observations of variability. For logistical reasons, the columns were placed in three groups within the laboratory (positions A to C, D to F, and G and H). The columns for continuous operation were selected using a random number generator within positions A through F due to access to electrical outlets for the pumps. The remaining columns were operated intermittently.

Three of the intermittent columns from the above experiments had supplementary sampling of selected parameters to observe the process of filter ripening. These columns were sampled on days 0, 3, 7, 10, 14, and 21. The three continuous columns were also sampled on these days, excluding day 10.

Generalized linear mixed modeling (GLMM) was used for statistical analysis in SAS 9.3 software (SAS Institute Inc., Cary, NC). The covariate of interest was the assigned treatment group.

5.4 Results

The effect of location in the laboratory (the "block" effect) was not statistically significant for any parameter and so was removed from the analysis. The blocks had been located within the same area of the laboratory, with no significant temperature gradient detected, and so no effect had been expected.

5.4.1 Continuous versus intermittent operation

The impact of intermittent versus continuous operation was large for removal of *E. coli* (1.67 $\log_{10}$ versus 3.71 $\log_{10}$) and MS2 (0.85 $\log_{10}$ versus 2.25 $\log_{10}$), and was highly significant ($p < 0.0001$) (Table 5-1).

Both sets of filters saw a reduction in NH_4^+-N as well as an increase in NO_3^--N as compared to influent and control samples. There was a smaller increase in NO_2^--N. These results suggest that nitrification was occurring within the filters, as has been noted elsewhere in the literature (Murphy et al., 2010b). However, the increased mass of NO_3^--N was larger than could be explained simply from the loss of NH_4^+-N. This may be accounted for by the decrease noted in organic N, suggesting the release of N through the decomposition of organic matter within the filter. The decrease of total nitrogen through the filters may be accounted for by the trapping of organic particles containing N.

The filter effluents were significantly different for all parameters other than pH and organic nitrogen (Table 5-1).

Table 5-1 Intermittent versus continuous effluent water quality. From 10 sampling days between days 28 and 58 of operation. Standard deviation in parenthesis, p-value represents comparison of intermittent versus continuous filter effluent

Parameter	**Influent**	**Control**	**Intermittent**	**Continuous**	***p*-value**
E. coli removal (log cfu)	n/a	-0.08 (0.31)	1.67 (0.51)	3.71 (0.59)	< 0.0001
MS2 removal (log pfu)	n/a	0.20 (0.23)	0.85 (0.45)	2.25 (0.45)	< 0.0001
Turbidity (ntu)	n/a	2% (37%)	87% (7%)	96% (3%)	< 0.0001
EC (μS)	100 (8)	104 (23)	123 (8)	136 (8)	< 0.0001
DO (mg/L)	8.7 (1.0)	7.8 (0.9)	6.5 (0.6)	8.0 (0.7)	< 0.0001
pH	7.6 (0.6)	7.4 (0.2)	7.6 (0.3)	7.7 (0.3)	0.1123
Total Nitrogen (μg/L)	1312 (44)	1269 (47)	1212 (68)	1137 (72)	< 0.0001
NO_3^--N (μg/L)	230 (105)	222 (93)	489 (72)	358 (125)	0.0073
NO_2^--N (μg/L)	16 (11)	11 (4)	20 (30)	35 (31)	0.0001
NH_4^+-N (μg/L)	110 (48)	185 (15)	20 (23)	34 (52)	0.0063
Organic N (μg/L)	956 (94)	850 (67)	682 (74)	711 (111)	0.8470

5.4.2 Filter ripening

Hydraulic conductivity

The filters in this experiment became clogged very quickly in the first two weeks of the experiment. This was likely due to algae and plant matter which had been observed in the influent water. In field settings, households which collect water from surface sources would use strategies to minimize the collection of such debris. All filters were maintained on day 15 (Figure 5-2), and the experimental protocol was modified to include straining influent water through a 6 mm sieve before dosing.

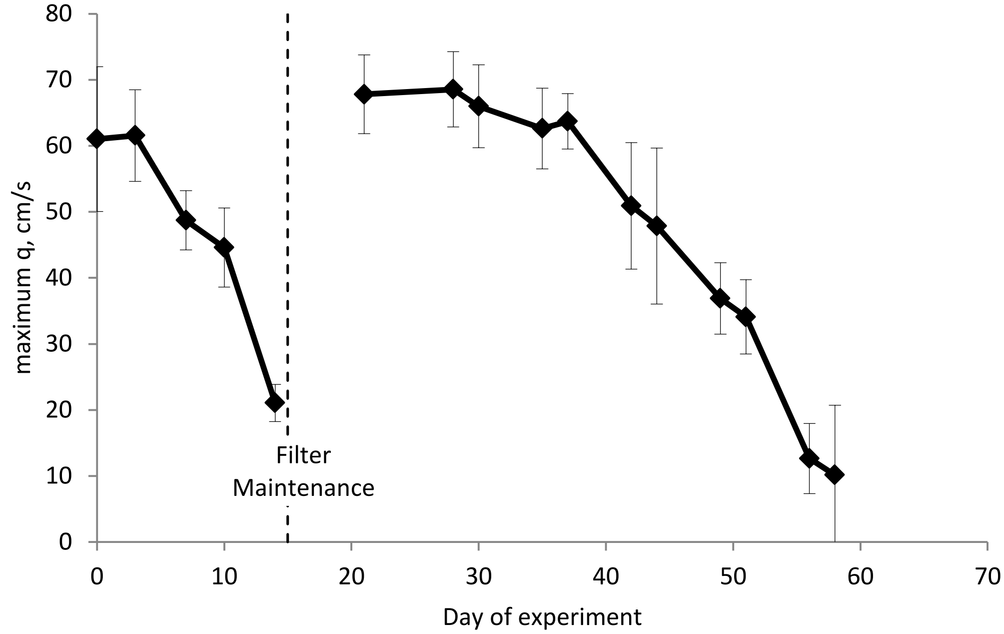

Figure 5-2 Average q_{max} by day of experiment for intermittent filters. Error bars indicate standard deviation. Days 0 to 21 include only three filters. Days 28 to 58 include all five intermittent filters.

The greatest change in hydraulic conductivity occurred within the first media layer, where the schmutzdecke formed (Figure 5-3). However, some level of clogging, as evidenced by reductions in hydraulic conductivity, occurred throughout the media bed. This trend was slight over the study period, and more evident in the 5 to 10 cm media layer than in those below. The hydraulic conductivity appeared to increase at all media depths immediately after maintenance, despite maintenance disturbing only the top 1 cm of media. This may have been because higher flow velocities through the filter in the days immediately following maintenance may have displaced and removed fine media particles.

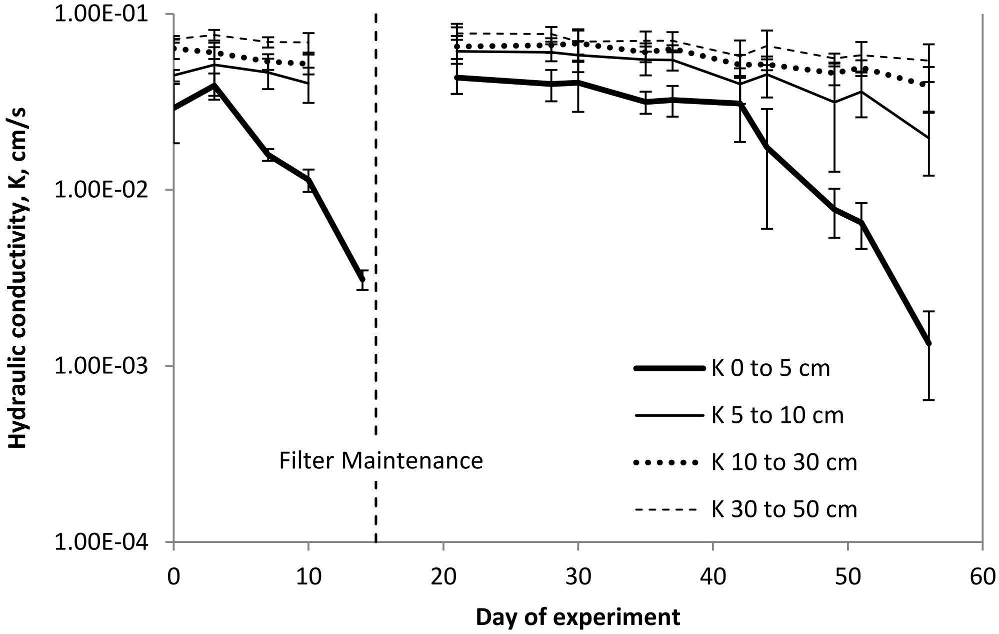

Figure 5-3 Hydraulic conductivity of media in intermittent filters by media layer

The piezometer tubes were not sensitive enough to detect the head loss between media layers in the continuous filters at the flow rates used in this experiment. By day 58 the flow rates in the intermittent columns were also too slow.

E. coli removal

E. coli removal in the filters was plotted over time. A best fit curve was developed to describe the plot, which was of the form:

$$y_t = a + b\frac{t}{t+c} \tag{5-2}$$

where

y_t	is the $\log_{10}$ *E. coli* removal on a given day,
t	is the number of days the filter had been in operation,
a	is the filter's initial removal capacity,
a + b	is the filter's maximum ripened removal capacity (when $\frac{t}{t+c} \rightarrow 1$),

c is a ripening factor.

The equation was calibrated for each treatment using two filters, then validated with the third filter (Figure 5-4).

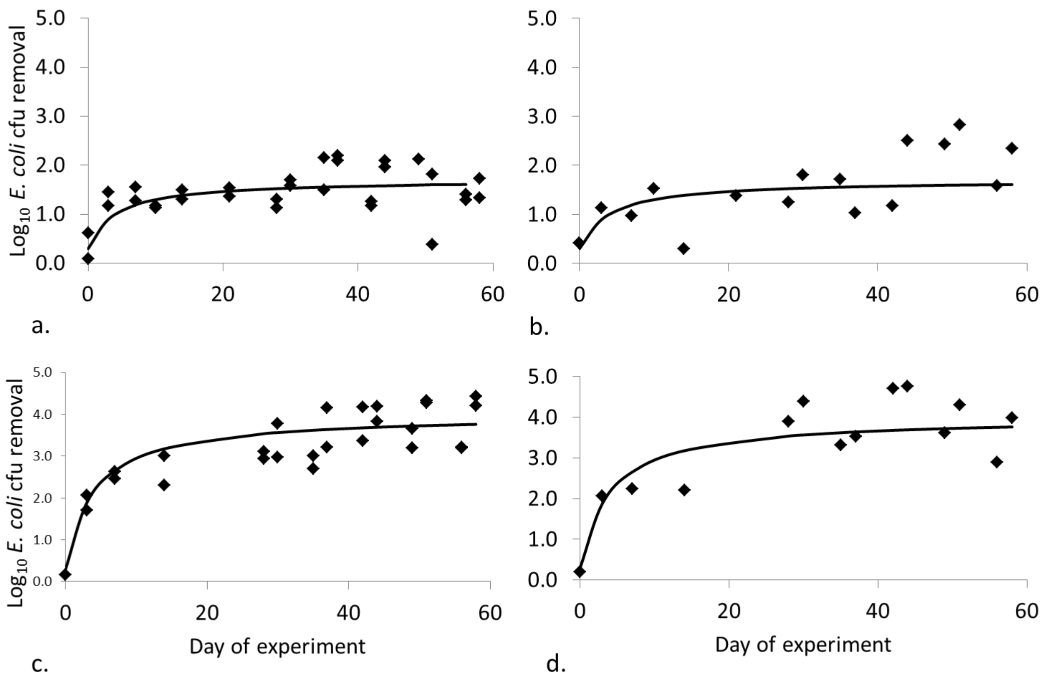

Figure 5-4 *E. coli* removal ripening curve. a - calibration of intermittent curve, b - validation of intermittent curve, c - calibration of continuous curve, d - validation of continuous curve

The value of *a* was common to both treatments as it was a function of the initial media parameters, and was set at 0.30 $\log_{10}$. After calibration, *c* was also found to be common to both treatments, and was set at four days.

As a + b was greater for the continuous group than the mean removal rates found in Table 5-1, these columns may not have reached their full removal capacity, and may have continued to slowly improve beyond the time represented in this experiment.

The model was tested through graphical observations of the residuals, and by calculating the coefficient of efficiency, *E* (Nash and Sutcliffe, 1970). An *E* value of one represents a perfect model fit; zero indicates a model no better than the mean; and lower values indicate a progressively worse prediction. Values between 0.5 and 1.0 are generally considered an acceptable fit.

The model fit the continuous filters well (Table 5-2), but was a poor fit for the intermittent filters. This may have been because the standard deviation was much higher for the intermittent group, making model fitting more difficult in general.

Table 5-2 Coefficients of efficiency, E, for ripening models

				E values	
Treatment Group	**a**	**b**	**c**	**Calibration curve**	**Validation curve**
Intermittent	0.3	1.35	4.0	0.36	0.30
Continuous	0.3	3.50	4.0	0.95	0.74

The model did not account for the possible effect of the day 15 filter maintenance on ripening. Most filters performed worse than the model predicted on the sample day immediately following day 15 (Figure 5-4), which is consistent with a maintenance effect.

Additional parameters

A ripening trend was not noted for turbidity, DO, or pH. EC was noted to follow a decreasing trend for all filters until day 21, at which point it stabilized. MS2 removal and nitrogen were not measured in the ripening portion of the experiment.

5.4.3 Depth sampling

Dissolved Oxygen

In continuous filters, nearly all DO consumption occurred between +1 cm and -5 cm (Figure 5-5a), where 0 cm represents the media surface. This range corresponds to the schmutzdecke. There was a large increase in DO between the bottom of the sand media, at only 0.6 mg/L (Figure 5-5a), to the filter effluent, at 8.0 mg/L (Table 5-1). This highlights the aeration effect of the outlet structure.

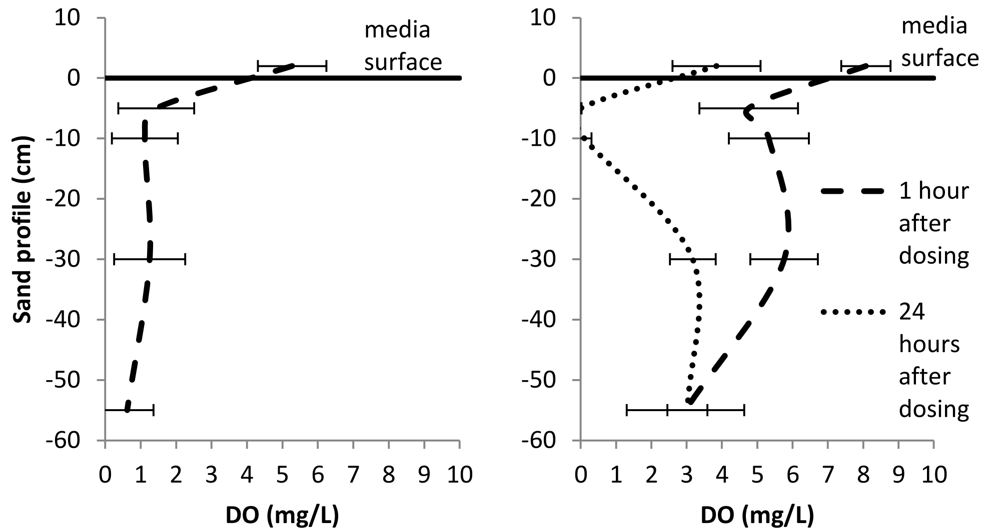

Figure 5-5 DO profile in a) continuous and b) intermittent filters. Error bars show standard deviation. 0 cm represents media surface.

The DO profile was more complex in intermittent filters (Figure 5-5b). Already at one hour after dosing, when flow rates were only just approaching 0 m/s, the oxygen profile did not continuously decline with depth, as would be expected with filtration and as was seen with the continuous filters. The DO at -5 and -10 cm was lower than that at -30 and -55 cm. This may have been due to the effect of the declining flow rates, where water from the beginning of the dose moved quickly through the schmutzdecke and more slowly through the deeper sand bed, while water towards the end of the dose spent more time within the schmutzdecke, allowing more time for oxygen consumption in this zone. By 24 hours after dosing, the DO immediately above the media surface had declined by 4 mg/L and at 30 cm below the media surface by 3 mg/L. The DO at -5 and -10 cm had dropped to 0 mg/L

Microbial removal with depth

For the continuous filters, the most effective zone for *E. coli* removal was the first 5 cm, corresponding to the schmutzdecke (Figure 5-6). The standing head was also a region of effective removal. Beneath 5 cm, there was a removal rate of 0.03 $\log_{10}$ for each additional centimeter of depth in the filter. For MS2, the schmutzdecke was also the location of most effective removal, but removal was also strong through the filter depth to 30 cm. Little MS2 removal occurred below 30 cm.

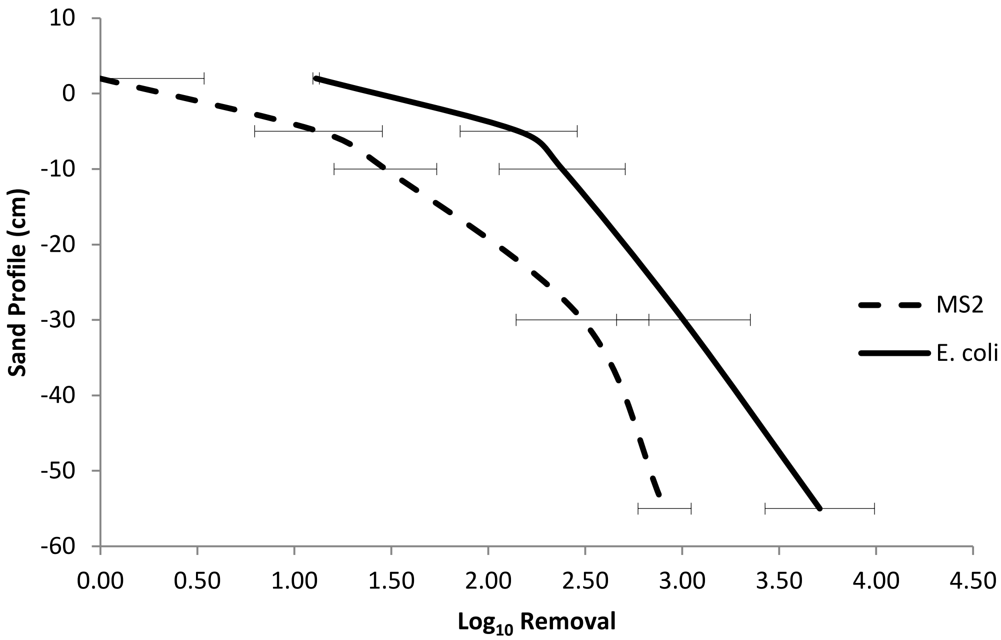

Figure 5-6 Removal by depth of microbial indicators for continuous filters. Error bars indicate standard deviation.

During the initial filtration step, *E. coli* removal in intermittent filters primarily occurred in the first 10 cm of filter depth, with little additional removal per centimeter of media depth beyond that (Figure 5-7). However, further removal did occur within the deeper media during the residence period up to 20 hours. There was little additional removal between 20 and 24 hours of residence time within the bed, though the standing head saw continued removal. Effluent grab samples indicated the best water quality for water which had spent the residence period at a 30 cm depth, and thus had a further 25 cm of filtration before the outlet at the end of the residence period. Water in the standing head had the highest removal over the residence period, but the lowest from grab samples. This may be due to re-suspension of settled microbes during the high initial flow rate during a filtration cycle.

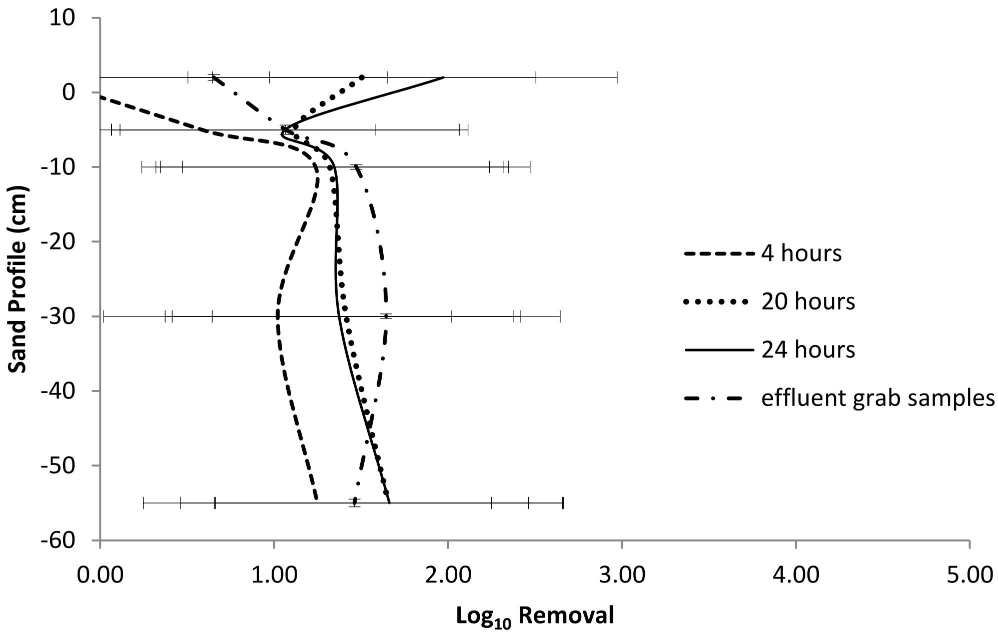

Figure 5-7 *E. coli* removal by depth in intermittent filters. Error bars indicate standard deviation.

MS2 removal in filters followed a different pattern than *E. coli* removal (Figure 5-8). The schmutzdecke played a much smaller role in removal, and little removal occurred during the residence time in the standing head. Bacteriophages are much smaller than bacteria, and so are less likely to settle by gravity in a free suspension. Most removal occurred during the residence period at 10 cm and 30 cm depths. Some re-suspension appears to have occurred after the residence period, as effluent grab samples had higher concentrations than the depth samples. MS2 removal was still occurring between 20 and 24 hours of residence time (Figure 5-9), indicating that further removal may be possible with extended residence times.

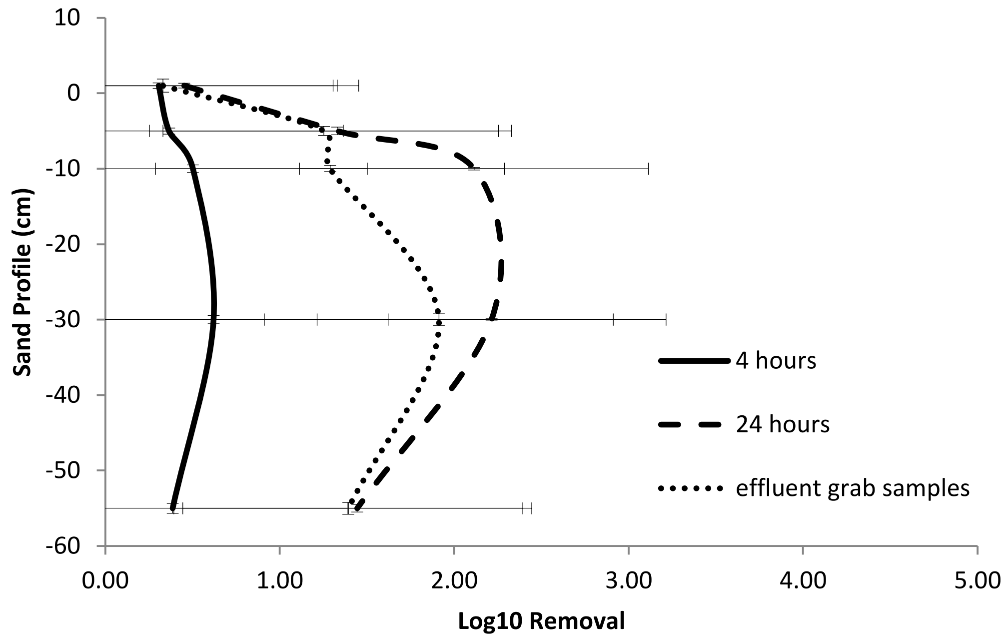

Figure 5-8 MS2 removal by depth in intermittent filters. Error bars indicate standard deviation.

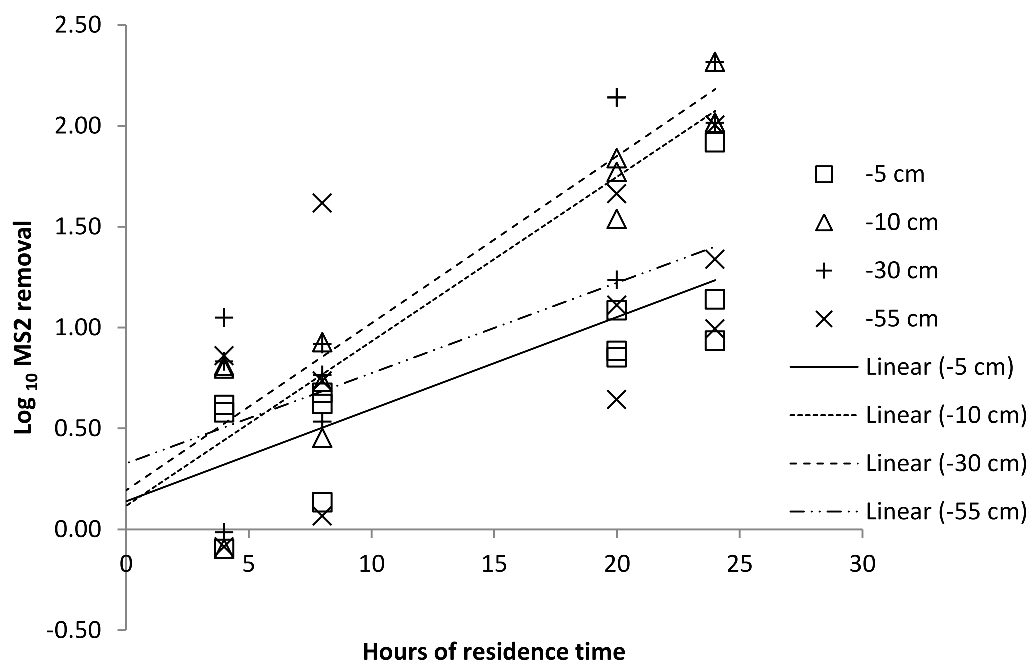

Figure 5-9 MS2 removal from sample ports over the residence period

Variability for the depth sampling was high for both *E. coli* and MS2. Further study with more columns, or more sample days per column, is recommended.

5.4.4 Deviation between intermittent filters

Selected water quality parameters for the five intermittent filters were compared from ten sample days between days 28 and 58, to determine within- and between-column variability (Table 5-3). Within-column variability describes the deviation for a particular column over the 10 sample days, while between-column variability describes the deviation between the five columns for any particular sample day.

Table 5-3 Standard deviations between intermittently operated columns

Parameter	Average within-column standard deviation	Average between-column standard deviation
E. coli removal (log cfu)	0.53	0.37
MS2 removal (log pfu)	0.45	0.26
Turbidity removal (%)	7%	3%
EC (µS)	8	3
DO (mg/L)	0.5	0.4
pH	0.3	0.3
N as NO_3 (µg/L)	73	28
N as NO_2 (µg/L)	31	6
N as NH_4 (µg/L)	19	11

The within-column standard deviations were higher than the between-column deviations, indicating that the variability caused by differences in water quality from day to day was larger than the variation caused by differences between the filters themselves.

For *E. coli* removal, the average within-column standard deviation was 0.53 $\log_{10}$, with a range of 0.38 to 0.75 $\log_{10}$. For a given filter, the difference between the best performing day and the worst performing day ranged from 0.88 to 2.21. The average between-column standard deviation was 0.37 $\log_{10}$, with a range of 0.08 to 0.89 $\log_{10}$. The difference between the best and the worst performing filters on a given day ranged from 0.2 to 2.45 $\log_{10}$.

This has important consequences for the interpretation of data from BSF studies with only one column per treatment. Small but significant effect sizes may be due to column effects as opposed to treatment effects. Likewise, caution must be taken in interpreting the results of experiments where filters are being compared which were run at different times or with different source water.

5.5 Discussion

Operating the filters intermittently led to a significant decrease in microbial water quality as compared to continuous operation. This is consistent with past SSF observations and recommendations in the literature (Huisman and Wood, 1974; Paramasivam et al., 1980). Although microbial removal rates did not match that of continuous operation, the intermittently operated filters were still effective at improving water quality, reducing *E. coli* by an average of 1.67 $\log_{10}$ (98%) and MS2 by an average of 0.85 $\log_{10}$ (86%).

Sampling at depth highlighted the differences between the two operating modes. Filtration through the schmutzdecke removed the largest rate of *E. coli* per centimeter depth in both cases. The remaining media column continued to remove *E. coli* in continuous filters, while it did not in intermittent filters during filtration but did during the residence period. The standing head was an effective removal zone for both continuous and intermittent filters. MS2 removal was similar to *E. coli* removal in the continuous filters, but without removal occurring in the standing head, and with less distinction in the removal rate between the schmutzdecke and the other parts of the media column. In intermittent filters, filtration was less effective than with continuous columns and the schmutzdecke was not more effective than other parts of the media column. The residence period was effective in phage removal. This is consistent with findings within the literature (Elliott et al., 2011).

Care must be taken when describing the BSF simply as a modified SSF (Fewster et al., 2004; Ngai et al., 2007; Vanderzwaag et al., 2009), as the mode of operation significantly impacts the effectiveness of the method. These results suggest that for intermittent operation, each additional centimeter of depth beyond the first 30 cm adds less removal efficiency than it does in continuous filtration, and it may be possible to experiment with changing the dimensions of BSF in cases where the existing filter's size creates challenges to household implementation (Chapter 4).

In this study, the difference between residence times of 20 and 24 hours was negligible for DO and reduction of *E. coli*, but MS2 removal continued during this period, suggesting that longer residence times may aid viral removal. This is consistent with previous studies (Elliott et al., 2011).

DO was expected to show a ripening trend, but did not. This may have been because of the extent of aeration that occurred in the filter outlet tube.

One limitation of this study was that in order to ensure that all filters received the same influent volume, the flow rate of the continuous filters was lower than that used in common practice. However, the alternative of increasing the volume filtered per day by the intermittent columns, either increasing the volume per dose or by increasing the frequency of dosing, has been found to have a detrimental effect on filter effluent quality.

The results of this study question some of the assumptions of BSF design, and highlight several areas for further research. The initial theory leading to the development of the BSF was that SSF effectiveness at reducing *E. coli* decreased because a deep standing head, as was the case in intermittent operation previously, led to anaerobic conditions within the schmutzdecke. As a result, reducing the standing head would in theory prevent these anaerobic conditions so that intermittent operation could achieve a similar performance to continuous operation (Buzanis, 1995). However, this study found that anaerobic conditions still occur in the schmutzdecke, and that intermittent operation of the BSF still performs poorly compared to continuous operation. A possibility for further research would be to test the role of the standing head depth on filter performance. Even with a diffuser plate, it was observed through the transparent column walls that some disturbance occurred to the media surface during dosing of intermittent filters, which did not occur in the continuous filters due to the low flow rate. A deeper standing head could reduce that disturbance. Field testing of filters has actually shown improved performance with deeper standing heads (Vanderzwaag et al., 2009), though this effect may have been due more to length of time since the filter had been maintained. Assumptions regarding optimal residence periods should also be further investigated.

5.6 Conclusions

- The biosand filter, like other slow sand filters, performs better at removing *E. coli* and MS2 bacteriophage under continuous operation than intermittent operation. However, intermittent operation still results in significant water quality improvements.
- MS2 is removed during continuous filtration up to at least 55 cm of media depth, but with reduced effectiveness at greater depths. In intermediately operated filters, MS2 is not removed during filtration, but rather during the residence time at all filter depths.
- Nitrification occurs in BSF under both continuous and intermittent operating conditions.
- Even with the reduced standing head of a biosand filter (5 cm), the top layer of filter media corresponding to the schmutzdecke may become anaerobic during the filter’s residence period.
- High standard deviations both from a single filter operated on different days, and between filters on the same day, mean that replicate columns operated in parallel are necessary for BSF experiments and that statistical

analysis must account for the lack of independence of observation from the same column by using methods such as repeated measures.

- Though most evident in the schmutzdecke, *all* media layers exhibit some decrease in hydraulic conductivity over a filter run. All media layers also exhibit some recovery of hydraulic conductivity after filter maintenance.
- The schmutzdecke provides the greatest *E. coli* removal during filtration for both intermittent and continuous BSF. However, continuous filters continue to see removal for each additional centimeter of filter depth, whereas after 10 cm, intermittent filters do not. Instead, further removal occurs with residence time within the filter.

5.7 Acknowledgements

Funding for this project was provided by the Caribbean Water Initiative (CARIWIN).

5.8 Connecting test to chapter 6

The field study presented in Chapter 4 identified extended residence periods as one possible reason for non-ideal performance of BSF. The present chapter investigates the impact of one, two, and three day residence periods on *E. coli* removal.

This chapter was prepared as a manuscript to be submitted to a peer-reviewed journal in 2013. It was co-authored by Dr. Chandra Madramootoo, who supervised the work. All literature cited in this manuscript is listed at the end of this thesis.

CHAPTER 6 Investigating the impact of multiday residence periods in biosand filters

6.1 Abstract

Operating conditions, including residence times, can significantly affect the performance of biosand filters. It is recommended to operate biosand filters with residence times of 1 to 48 hours. However, a field study in Guyana found that households operated their filters with residence periods of one to seven days, with a mean of three days, or 72 hours, which is above that recommended. Laboratory studies to date have looked at the impact of residence periods of 6 to 36 hours, with no studies extending to 48 hours, or investigating whether biosand filter performance decreases beyond 48 hours. The goal of this study was to compare *Escherichia coli* removal in filters operated with one-, two-, and three-day residence periods. Nine laboratory-scale filters were operated in parallel, with three replicates for each of the three residence periods. Filters were fed with lake water supplemented with *E. coli* strain B (ATCC# 11303). Influent, effluent, and control samples were tested for a range of parameters including *E. coli* colony forming units; turbidity; pH; electrical conductivity; dissolved oxygen; and nitrogen as ammonia, nitrate, and nitrite. Hydraulic conductivity and dissolved oxygen of pore water were measured for different sand depths within the filters every six days. The study found no significant difference in *E. coli* removal by extending the residence period. However, water treated in filters with increased residence periods had lower dissolved oxygen concentrations, with portions of the filter becoming anaerobic, and bearing increased nitrite levels.

6.2 Introduction

Biosand filters (BSF) are considered to be one of the most promising household water treatment technologies presently available (Sobsey et al., 2008). Laboratory trials have demonstrated the effectiveness of BSFs at removing >5 $\log_{10}$ Giardia cysts, 3.7 $\log_{10}$ Cryptosporidium oocysts (Palmateer et al., 1999), 1.9 $\log_{10}$ *Escherichia coli*, and an average of 0.5 $\log_{10}$ for bacteriophage (Elliott et al., 2008). Randomized controlled field trials in Cambodia (Stauber et al., 2012b), Kenya (Tiwari et al., 2009), and the Dominican Republic (Stauber et al., 2009) have shown significant reductions in diarrhoeal disease associated with BSF use.

BSFs are biologically active granular media filters that are operated intermittently, and thus do not require continuous pumping. The filter is designed to operate such that a batch, or dose, of influent water is added all at once, creating a pressure head which drives flow. The new dose enters the interstitial spaces of the granular media. The filter effluent is composed of water from the previous dose, which has been displaced by the new dose. As filtration progresses, the pressure head decreases, reducing flow until it eventually stops. The period between doses is known as the residence period. The filter outlet is constructed such that the media remains saturated during the residence period. During the first weeks of operation, the schmutzdecke, or filter cake, develops and the filter's capacity to remove microorganisms improves. This is referred to as filter ripening.

BSFs in field trials have been found to significantly improve water quality, but with smaller and more variable *E. coli* reductions than in laboratory trials (Fiore et al., 2010; Vanderzwaag et al., 2009). Operational factors, including the frequency of dosing, were suggested as a cause of high variability in *E. coli* removal (ranging from 0 to 99.7%) found during a field test of BSFs in the Dominican Republic (Stauber et al., 2006).

The present recommendation for BSF operation is to dose the filter between one and four times a day, with a minimum residence period of one hour and a maximum of 48 hours (CAWST, 2012). However, a study on BSF use in Guyana (Chapter 4) found that households operated their filters with residence periods of one to seven days with a mean of three days, which is larger than that recommended.

Only two studies in the peer-reviewed literature investigated the impact of residence periods on BSF removal of bacterial indicators, both of which were laboratory studies. Baumgartener et al. (2007) compared a BSF operated with 12- and 36-hour residence periods, and found significantly better total coliform removal with 12-hour operation. However, their study was limited in that it used a single filter with changing conditions. The BSF was first operated for 30 days with 12 hour dosing in order to ripen the filter. It was then operated under the different experimental conditions and the filter effluent sampled for total coliforms.

Jenkins et al. (2011) compared 5- and 16-hour residence periods in separate BSFs, with improved fecal coliform removal occurring with the longer residence period. However, their "long" residence period was still shorter than one day.

No studies in the literature extend residence periods to two days or beyond. It has been predicted that residence periods longer than 48 hours, or two days, will lead to nutrient depletion and starvation of the biolayer (CAWST, 2012).

The goal of this study was to compare BSFs operated with residence periods of one, two, and three days for *E. coli* removal, dissolved oxygen (DO) profiles, and evidence of nitrification.

6.3 Materials and methods

6.3.1 Experimental design

A randomized complete block design with three treatments was used for this experiment. The treatments were one-, two-, or three-day residence times. The three blocks were based on location on the laboratory counter to account for any possible differences in environmental conditions (Figure A-8).

The experiment ran for 84 days from November 2011 to February 2012.

Laboratory-scale column filters were constructed rather than full-scale BSFs to enable running the nine units in parallel (Elliott et al., 2011).

6.3.2 Filter design

There are several different models of BSFs being produced. The filters for this experiment were designed to replicate the vertical dimensions of the CAWST V10 filter (CAWST, 2012). They were constructed of 10 cm diameter transparent acrylic tubing.

Filters had DO sensors and piezometer tubes installed at locations corresponding to 1 cm above the sand surface, and 5, 10, 30, and 55 cm below, as illustrated in Figure 6-1. The diffuser plate was installed 2 cm above the standing head. In order to prevent algal growth, filters were covered in black plastic throughout the experiment when not being dosed or measured. As field biosand filters are constructed of concrete or opaque plastic, covering the transparent columns better represented field conditions.

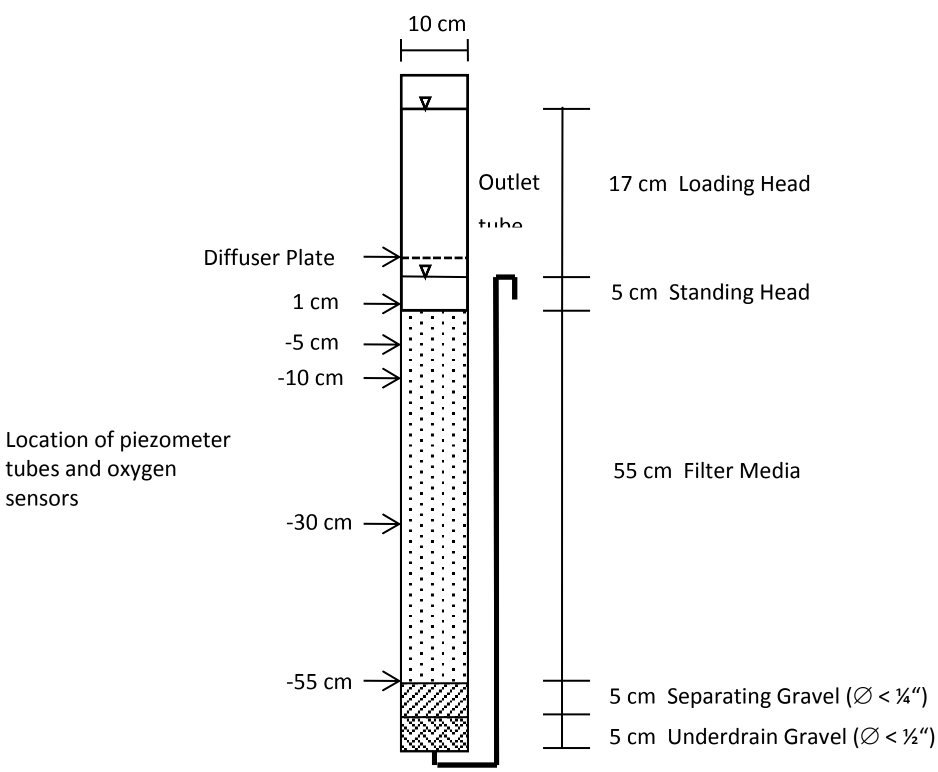

Figure 6-1 Schematic of laboratory filters

The filter media was composed of locally purchased sand. The media had a porosity of 0.42, maximum diameter of 0.7 mm, effective diameter (d_{10}) of 0.17 mm, and a uniformity coefficient (UC) of 2.06.

The two underdrain layers were composed of locally purchased crushed gravel that was washed and sieved so that the fine top layer had a diameter range of 0.7 to 6.4 mm and the coarse bottom layer had a diameter range of 6.4 to 12.7 mm.

In order to prevent air binding, the filters were partially filled with water before adding the media to the desired depths, as occurs in field installation of full-sized BSFs (CAWST, 2012). As air bubbles would be a particular problem for the piezometer tubes in these filters, the distilled water used in this experiment was first boiled to decrease the saturation point of air in water and so allow much of the air to be released. It was then cooled to room temperature and slowly introduced through the outlet tube in order to prevent the introduction of air through splashing or turbulence.

As with the V10 filter, the dosing volume was set to be equivalent to the pore volume of the sand, in this case 1.8 L. The total volume of water remaining in the filter during the residence period including the standing head, sand pore volume, underdrain pore volume, and outlet tube, was approximately 2.5 L.

6.3.3 Influent water

In November and December of 2011, water was collected daily from Lac St Louis, Quebec. The water was stored overnight to bring it to room temperature. After the lake ice thickness increased beyond 20 cm, water was only collected weekly and then stored frozen at an outdoor location until two days before dosing, when it was brought indoors to thaw and reach room temperature. Influent temperature was $19.9 \pm 0.9\ ^{o}C$.

Influent water was supplemented with *E. coli* strain B (ATCC # 11303) each day before dosing. Each week new cultures of *E. coli* were grown in tryptic soy broth to log phase (5 hours at 37° C), divided into daily aliquots, and refrigerated at 4°C.

6.3.4 Filter dosing

Filter dosing followed a six-day cycle in order to accommodate the three residence periods (Table 6-1).

Table 6-1 Dosing schedule for treatment groups, where day 0 corresponds to day 6 of the previous cycle

Day of Cycle	One-Day Group	Two-Day Group	Three-Day Group
0	X	X	X
1	X		
2	X	X	
3	X		X
4	X	X	
5	X		
6	X	X	X

Water entering the filter during any given dose theoretically corresponded to water exiting the filter in the subsequent dose.

6.3.5 Measurements and sampling

Filter effluent samples were taken from filters from all treatment groups on each cycle day six, with the exception of three missed *E. coli* sample days over the holiday period. All samples from the filters were well-mixed samples taken one to two hours after dosing, after 1.4 to 1.8 L had filtered, indicating that filtration was 80% to 100% complete.

The influent samples for the treatment groups were taken from the dose prior to that of the effluent sample. For the one-day group, this corresponded to cycle day five. For the two-day group this was cycle day four, and for the three-day group this was cycle day three (Table 6-1).

Five supplementary test days were added in which all filters received the same influent water, and were then sampled at their following dose. There was no difference in results between the two types of sampling (different influent but same test day versus same influent but different test day) and so the results were pooled for analysis.

Control samples were collected periodically through the experiment. A portion of influent water was set aside in a loosely-capped, sterile, glass media bottle, wrapped in black plastic, and kept beside the filters on the laboratory bench for one, two, or three days. The samples were then analyzed with their corresponding filters.

Instantaneous flow rate, q, was analyzed by taking the derivative of the fitted curve of time versus water level for the top piezometer tube. Hydraulic conductivity, K, was analyzed by taking the slope of the linear fitted curve of the head difference between the two piezometers of interest divided by the distance between them, versus q, following Darcy's law.

E. coli colony forming units (cfu) were enumerated with m-coliblue24® broth (Hach Company, Loveland, CO) using the membrane filtration method (APHA et al., 1998).

Turbidity was measured using a Lamotte 2020e turbidimeter (Lamotte Company, Chesterton, MD). Temperature, electrical conductivity, pH, and DO were measured using a YSI 556 multimeter (YSI Inc., Yellow Springs, OH).

In-situ DO measurements were taken with RedEye® oxygen patches read with a Neofox fluorescence probe (Ocean Optics, Dunedin, FL). This is a non-intrusive method: readings were taken through the transparent acrylic filter wall. Sensors were individually calibrated after being installed, but before media placement, by filling filters with distilled water and bubbling with Nitrogen gas until DO concentrations of 0 mg/L were confirmed throughout the filter with the YSI 556 multimeter.

Nutrient samples were taken every six days from influent and filter effluent samples until day 60, with the exception of one missed sample day over the holiday period. Hach methods TNT 830, TNT 835, and 8507 were used with a DR-2800 Spectrophotometer to measure nitrogen as ammonia, nitrate, and nitrite respectively (Hach Company, Loveland, CO). Total nitrogen samples were acidified with hydrochloric acid and stored at 4°C until the end of the experiment and measured using the perchlorate method (APHA et al., 1998).

6.3.6 Tracer Tests

Two sets of tracer tests were performed on the filters. The first was to test the filter design for short-circuiting. The second was to assess the operational conditions of the experiment.

For both sets of tracer tests, the filters were first rinsed several times with distilled water. The tracer selected was a solution of 200 mg/L NaCl in distilled water. Grab samples were taken from filter effluent every 100 mL and measured for EC as a proxy for NaCl concentration (Elliott et al., 2008). The tracer was followed by doses of distilled water.

In the first test, the standing head was decanted from the media surface before doses were applied (Elliott et al., 2008). As such, this test did not represent a filter in operation, but rather tested the hardware of the laboratory filters.

The second tests were under experimental conditions, with a 5 cm standing head and a 1.8 L dose volume. Each dose was added to the filter up to a maximum 17 cm loading head (Figure 6-1). It was not possible to apply the full dose at once. The remaining portion was added after the loading head had decreased by 3 cm.

After at least 1.7 L of water had filtered (corresponding to a loading head below one cm), the next dose was applied. This was repeated until effluent EC had returned to pre-tracer levels.

6.3.7 Statistical analysis

A statistical analysis was performed using generalized linear mixed modeling (GLMM) in the statistical software SAS 9.3 (SAS Institute Inc., Cary, NC).

GLMM was selected in order to control for possible environmental differences within the lab (blocking effect), and the lack of independence between measurements from the same filter (repeated measures). The covariate of interest was the assigned treatment group.

6.4 Results

6.4.1 Tracer tests

The short–circuiting tracer tests indicated that, like with full-sized BSFs, the laboratory filters functioned as plug flow reactors (Elliott et al., 2008), with a Morrill dispersion index of 1.8.

Under experimental conditions, with a 5 cm standing head and 1.8L dosing volume, the tracer tests required four doses to complete (Figure 6-2). In the first dose, the tracer entered the standing head and upper media pores, with no tracer detected in the effluent. Forty-eight percent of the cumulative tracer volume had exited the filter by the end of the second dose, with 96% by the end of the third. The final 4% exited the filter in the fourth dose, as is illustrated by the dashed "cumulative tracer fraction" line.

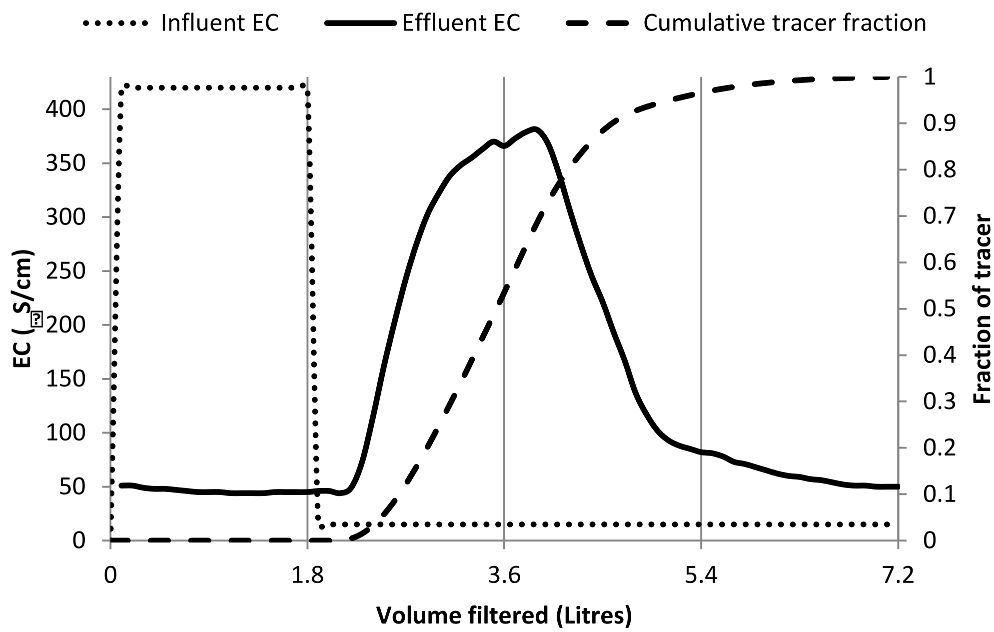

Figure 6-2 Tracer test results

Supplementary tracer tests after the experiment on each of the filters did not indicate the development of short-circuiting. However, a slight shift in the curve did occur. The results were 0% of tracer exiting in the first dose, 53% in the second, 97% by the third, with the remainder exiting in the fourth, suggesting that there had been some settling of media and removal of fine material during the experiment. These fractions were common to all treatment groups (p = 0.8252), with a standard deviation of less than 0.1%, indicating that the filters were very similar in construction, media placement, and thus pore volume.

Because the short-circuiting tests indicated plug flow within the media, it was assumed that most mixing occurred within the standing head. The first approximately 0.4 L of water exiting the filter during the second dose did not contain the tracer. This indicates that each new dose does not completely displace the pore water in the filter. The 0.4 L can be accounted for by 0.02 L of water that would have been in the outlet tube, 0.28 L in the gravel underdrain, and an additional 0.1 L in the bottom of the sand profile, corresponding to the media depth range of 52 to 55cm from the surface. This would include the bottom piezometer tube and DO sensor.

6.4.2 Dissolved oxygen profile

The dissolved oxygen profiles (Figure 6-3) confirm that oxygen is consumed throughout the media profile over time, not only within the schmutzdecke. The rate of oxygen consumption at different depths differed by treatment group. For all depths other than 55cm, the one-day group had lower DO at one hour after dosing. This indicates that more oxygen had been consumed during the filtration step and/or the early residence period in those filters. For both the two- and three-day residence period groups, DO from the first sensor, approximately 1 cm above the sand surface, reached a minimum concentration 24 hours after dosing, then slowly increased. Although the mean DO remained above 0 mg/L for all treatment groups at all depths, for both the 2- and 3- day filters the 5 cm and 55 cm depth sensors were frequently at 0 mg/L, as can be seen by the error bars in Figure 6-3.

The 55 cm depth sensor must be interpreted cautiously because, as the tracer test indicated (Figure 6-2), it corresponds to water that was not introduced in the same cycle as the other sensors.

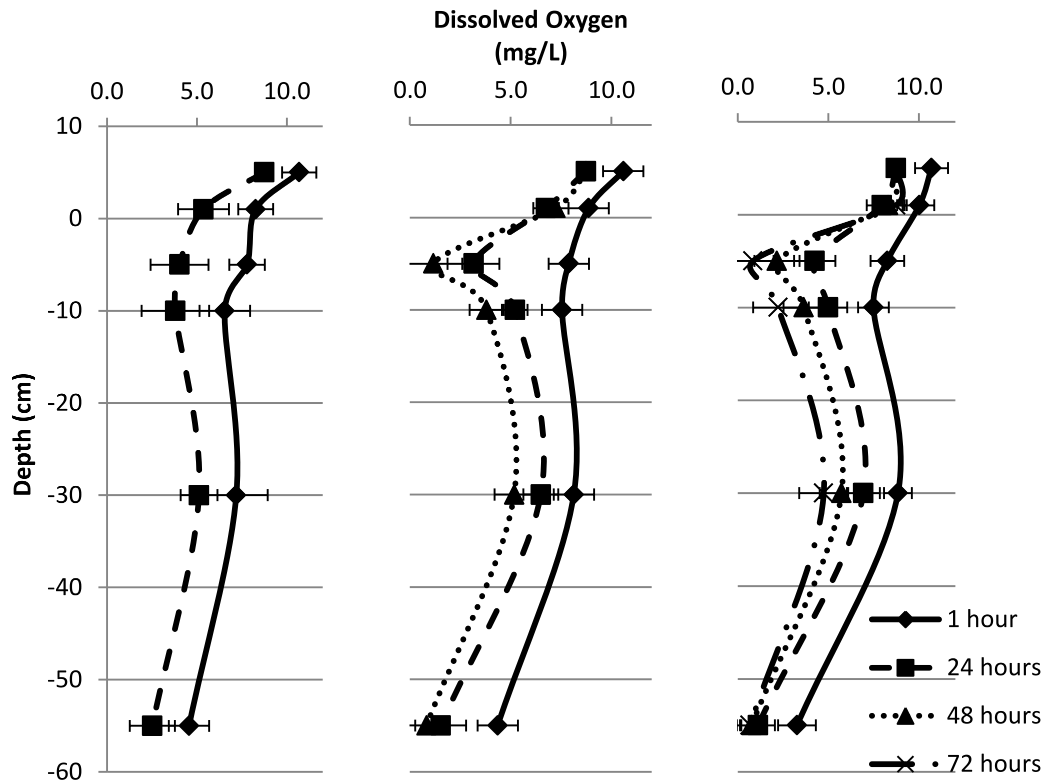

Figure 6-3 DO profiles over time in treatment groups 1, 2, and 3 respectively. Error bars indicate one standard deviation.

6.4.3 Water quality

Table 6-2 presents the results of the water quality analysis of influent and control samples. Paired t-tests were used to compare control samples to their corresponding influent sample. Water in the control samples had decreasing DO, and increasing Nitrogen as NO_2^- and NH_4^+, with time. *E. coli* concentrations also tended to decrease with time after the first day, with marginal reductions on the second day (p=0.051), and significant reductions by the third (p=0.034).

Table 6-2 Influent and control sample water quality parameters. Mean ± standard deviation (number of samples)

Parameter	**Influent**	**1 Day Control**	***p***	**2 Day Control**	***p***	**3 Day Control**	***p***
E.coli, $\log_{10}$ cfu/mL	2.1 ± 1.2 (46)	2.1 ± 1.1 (8)	0.851	1.4 ± 1.8 (8)	0.051	0.0 ± 1.3 (7)	0.034
Turbidity, NTU	3.4 ± 1.5 (65)	4.0 ± 2.0 (7)	0.666	3.3 ± 2.0 (9)	0.050	2.9 ± 1.9 (8)	0.895
DO, mg/L	10.6 ± 0.9 (63)	8.5 ± 0.3 (6)	0.001	8.06 ± 0.3 (9)	0.000	7.0 ± 0.7 (7)	0.000
EC, µS/cm	117 ± 23 (65)	135 ± 5 (6)	0.388	122 ± 18 (9)	0.183	121 ± 17 (8)	0.216
pH	7.4 ± 0.2 (63)	7.5 ± 0.1 (7)	0.784	7.6 ± 0.2 (9)	0.155	7.5 ± 0.2 (7)	0.427
N_{org}, µg/L	342 ± 124 (18)	-	-	-	-	-	-
NO_3^--N, µg/L	459 ± 102 (25)	476 ± 113 (6)	0.656	463 ± 105 (7)	0.684	413 ± 79 (7)	0.283
NO_2^--N, µg/L	6 ± 3 (28)	9 ± 3 (7)	0.038	10 ± 4 (8)	0.016	12 ± 5 (8)	0.002
NH_4^+-N, µg/L	93 ±21 (28)	151 ± 14 (7)	0.000	176 ± 34 (8)	0.000	181 ± 67 (8)	0.000

There was no significant difference in *E. coli* removal between filters run with one-, two-, or three-day residence periods (Table 6-3). There were, however, significant differences in effluent quality in terms of turbidity, DO, EC, NO_3^--N, and NO_2^--N.

The difference in effluent DO between treatments corresponds to the differences in the dissolved oxygen profile illustrated in Figure 6-3.

All treatment groups exhibited increased EC and pH as compared to the influent. When noted in previous studies, this phenomena has been attributed to calcium carbonate leaching from the concrete filter box (Murphy et al., 2010a). As the filters in this study were constructed of acrylic rather than concrete, the effect is more likely due to leaching from the filter media rather than the filter walls. Water with a longer contact period with the media (i.e. longer residence period) had a greater EC increase.

After ripening, all filters exhibited similar levels of nitrification, with decreased NH_4^+ concentrations in all filters as compared to the influent, and no significant difference between groups. Denitrification also appears to have occurred, with decreasing total nitrogen and increasing NO_3^- in all filters. This is consistent with other studies (Murphy et al., 2010b). Denitrification played an increased role in the treatment groups with longer residence periods, with significantly lower NO_3^--N remaining in three-day filters, and significantly higher NO_3^--N in one-day filters (Table 6-3). Denitrifying microbes prefer oxygen-poor environments, which were more likely to occur in the two- and three-day filters (Table 6-3).

Table 6-3 Water quality of one, two, and three day residence periods. Mean ± standard deviation (number of samples)

Parameter	**1 day residence period**	**2 day residence period**	**3 day residence period**	**p value**
E .coli (Log_{10} removal)	1.8 ± 0.8 (38)	1.9 ± 0.8 (41)	1.8 ± 0.9 (37)	0.235
Turbidity, NTU	2.7 ± 0.7 (48)	2.2 ± 1.0 (47)	1.3 ± 0.4 (47)	<0.001
DO, mg/L	7.2 ± 0.5 (48)	7.1 ± 0.3 (47)	6.7 ± 0.4 (47)	<0.001
EC, µS/cm	155 ± 21 (48)	157 ± 19 (47)	163 ± 16 (47)	<0.001
pH	8.0 ± 0.1 (48)	8.0 ± 0.1 (47)	8.0 ± 0.1 (47)	0.600
N_{org}, µg/L	149 ± 69 (18)	154 ± 94 (18)	161 ± 88 (17)	0.109
NO_3^--N, µg/L	630 ± 69 (18)	611 ± 58 (18)	543 ± 56 (17)	<0.001
NO_2^--N, µg/L	3 ± 2 (18)	6 ± 5 (18)	14 ± 10 (17)	<0.001
NH_4^+-N, µg/L	11 ± 5 (18)	10 ± 5 (18)	10 ± 5 (17)	0.559

6.4.4 Hydraulic loading rate

The maximum hydraulic loading rate, q_{max}, in the filters at the onset of the experiment, with a 17 cm loading head, was 0.72 ± 0.06 m/h. This is much higher than the 0.2 m/h maximum flow rate recommended for conventional slow sand filters (Crittenden et al., 2005), but lower than the 1.1 m/h noted elsewhere for BSFs (Elliott et al., 2006). The q_{max} declined through the experiment as the filters began to clog for all treatment groups (Figure 6-4). The decline was largest for filters in the one-day group when the filters were compared by day of the experiment (Figure 6-4), but was similar for all treatment groups when compared instead by the number of times the filter had been dosed (Figure 6-5).

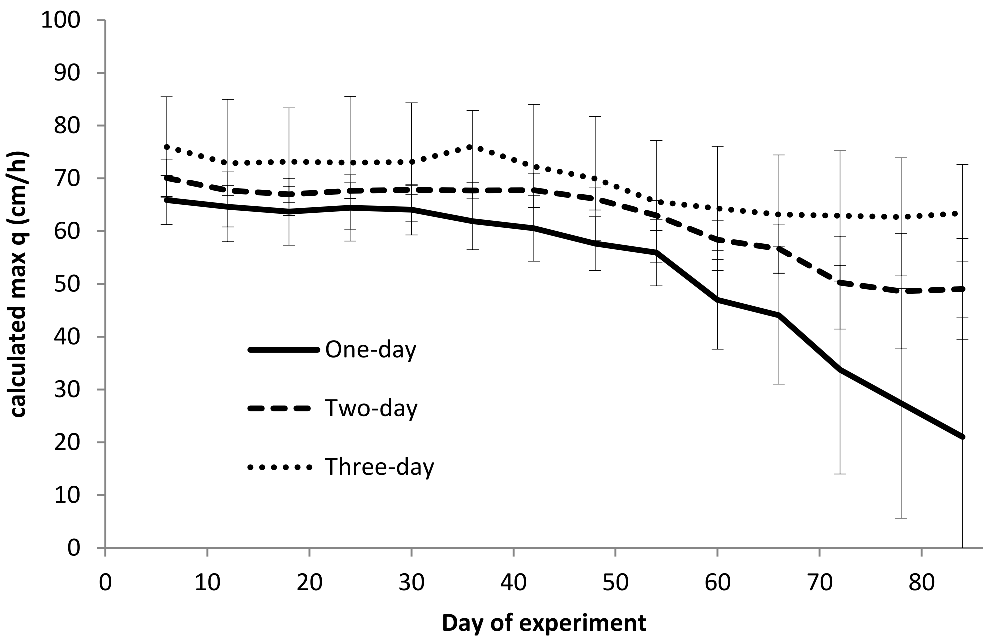

Figure 6-4 Maximum hydraulic loading rate versus day of experiment

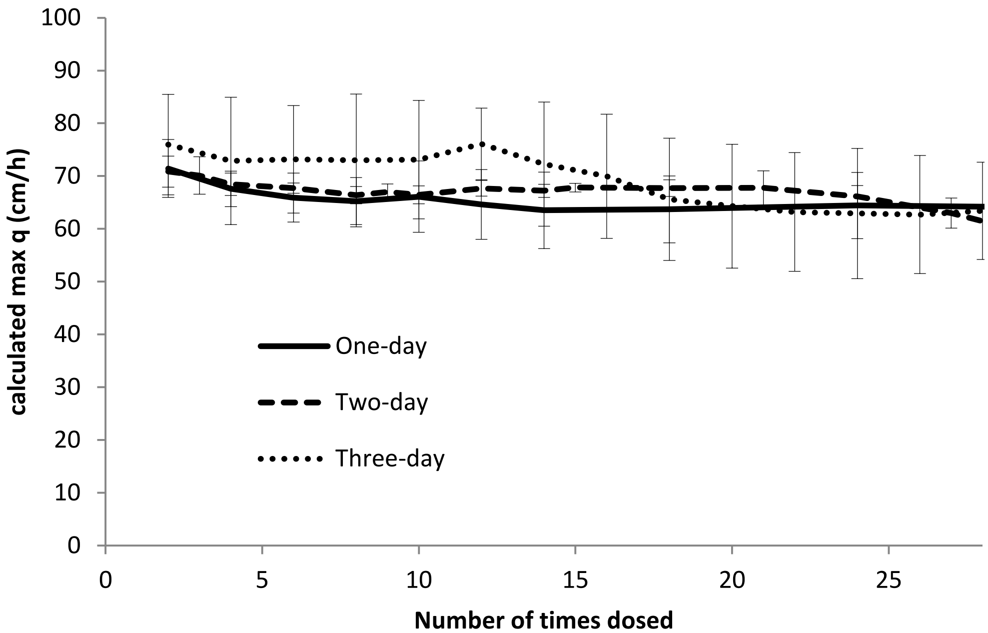

Figure 6-5 Maximum hydraulic loading rate versus number of times filter had been dosed

The hydraulic conductivity (*K*) of the media was highest towards the bottom of the filters (3.6×10^{-5} m/s) and lower towards the top (8.8×10^{-5} m/s), even before filter ripening. This was likely related to the installation method, and would also occur in full-scale field BSFs. During installation, it was observed that fine particles would remain in suspension while coarser particles would quickly settle. This resulted in some layering of the media which could be observed through the transparent column walls, and may have led to a gradient of particle size through the filter depth.

Hydraulic conductivity declined as the experiment progressed at all media depths, not only at the layer containing the schmutzdecke, as was also noted in Chapter 5.

6.4.5 Influence of the laboratory environment

A temperature gradient was found to exist in the laboratory, with the average effluent temperatures from Block 1 filters being 0.4°C warmer than those of

Block 3 filters. Location within the laboratory had a small but statistically significant effect on *E. coli* removal, turbidity, pH, and NO_3^--N.

Block 1, consisting of the three filters nearest the laboratory refrigerator and furthest from the door, had higher *E. coli* removal (p=0.013) as compared to block 2, but also higher effluent turbidity (p=0.024). Block 1 filter effluent had significantly lower pH than both blocks 2 and 3 (p<0.001 for each). Block 3 had significantly lower NO_3^--N than Blocks 1 (p=0.012) and 2 (p=0.022).

6.5 Discussion

An advantage in this experiment was the supersaturated DO levels found in the influent water, especially late in the experiment. Outdoor temperatures ranged from a daytime high of 14°C in November to an overnight low of -24°C in January. Saturation levels for DO are much higher at lower temperatures and DO levels did not fully drop to saturation levels for the laboratory temperatures of approximately 20°C before dosing, even after sitting at room temperature for two days. Thus the experiment occurred with higher DO than is typical in tropical environments. This allowed for the visualization of the progressive decline of DO within the media profile over time under the one-, two-, and three-day residence periods. In conditions with lower influent DO, some regions of the filter may be anaerobic after only 24 hours (Chapter 5). A physical limitation to the filters in this experiment was that the closest oxygen sensor to the schmutzdecke within the media profile was 5 cm below the sand surface. The DO consumption peak likely occurred within the schmutzdecke, or between the sand surface and the -5 cm sensor.

6.5.1 Nitrification

It is unclear at which depth nitrification and denitrification occurred within the filter media. Murphy et al. (2010b) hypothesize that nitrification occurs within the schmutzdecke during filtration, while denitrification occurs within the media depth during the residence period. This was based on the assumption that the majority of DO in influent water is consumed by the schmutzdecke during filtration, leaving the media column nearly anaerobic for the entire residence period. The present experiment questions that assumption for most situations. Approximately 2 mg/L of DO was consumed during filtration, leaving most of the filter depth aerobic. The decreasing DO levels during the residence period suggest the presence of aerobic microorganisms in the media. This is consistent with Elliott et al (2011) attributing bacteriophage reduction at depth in BSFs to aerobic microbial processes. The regions most likely to develop anaerobic zones were the top few centimetres of sand that house the schmutzdecke and the bottom of the media where some portion of water was remaining from previous filtration cycles. However, in special cases such as Murphy et al. (2010), where influent DO levels were lower than 2 mg/L, it is possible that anaerobic processes dominated within the filter bed.

Nitrate and nitrite concentrations for all filters remained well below the WHO guideline values of 11 mg/L NO_3^--N and 0.9 mg/L NO_2^--N (WHO, 2011). However, influent total nitrogen in this experiment was also very low (< 1 mg/L). In cases where influent nitrogen levels are high, as with Murphy et al. (2010b), it would be important to consider the effect of increasing nitrite in filter effluent with increasing residence period.

6.5.2 Location

The significant impact of laboratory location was unexpected, as all filters were placed in a row on the same laboratory bench, for which conditions would vary only slightly. However, the sensitivity of other biologically active filters, such as conventional slow sand filters, to temperature has been well documented (Jabur, 2006; Petry-Hansen et al., 2006; Ungar and Collins, 2008). Block 1, the block with the highest *E. coli* removal, was placed nearest to the laboratory refrigerator, which may have acted as a heat source. The difference in performance reached statistical significance, but the magnitude of the effect was small, as might be expected with a small but consistent temperature difference.

6.5.3 Limitation

One limitation to this study is that all treatment groups were operated consistently throughout the experiment, meaning that the one-day filters were always dosed every day, and the three-day filters every three days. These results cannot be extrapolated to the case where a filter matured under one set of conditions is then operated under a different set of conditions.

6.6 Conclusions

- *E. coli* removal was not significantly impacted by increasing the length of the residence period in the BSF from one day to two or three days.
- Longer residence periods led to reduced dissolved oxygen in filter effluent and throughout the filter profile.
- Longer residence periods led to increased nitrite concentrations in filter effluent.
- When dosing volumes are equivalent to sand pore volume (approximately 70% of total water volume in the filter), approximately half of the filter effluent corresponds to influent from the previous dose while the remaining originates from earlier doses. This may lead to anaerobic conditions developing at the bottom of the filter media profile.
- Further studies are necessary to understand the role of temperature on filter performance.

6.7 Acknowledgements

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CHAPTER 7 Summary and Conclusions

7.1 Summary

HWTS technologies provide an interim solution to drinking water quality in areas which are not yet serviced by a continuous piped connection to a communal treated source. BSF is one promising technology available for this purpose.

The overall goal of this research was to better understand, and thus improve, the BSF for field operation.

Objective 1: Compare the performance and sustainability of BSF with other HWTS methods, namely ceramic candle filters and hypochlorite solution, in the village of St. Cuthbert's Guyana.

A baseline study of water, sanitation, and hygiene was undertaken in the Amerindian community of St. Cuthbert's, Guyana consisting of testing of community water sources for thermotolerant coliforms, testing of household drinking water quality, and a household questionnaire. This study identified that water was a factor in diarrhoeal disease in the community, that household drinking water quality was impacted by post-collection contamination, and that this community could benefit from household water treatment and safe storage technologies (Chapter 3).

BSF performed poorly in the field study as compared to ceramic candle filters and hypochlorite solution, both in terms of sustained usage (4% as compared to 36% and 20% respectively) and water quality of treating households, where the households using the filter did not have significantly better water than control households with no treatment.

In a survey of the entire community after the study was complete, including households which had not received any water treatment technology, biosand filters were found to be the least popular treatment method, with 39% of households stating that they would prefer having no treatment to receiving a biosand filter.

Three filters which were tested in the field for 28 days were able to reduce thermotolerant coliforms from creek water, but the results had high variability.

The main reasons that community members identified for not liking the filter were: 1) it was too big and heavy; 2) they didn't trust it, mostly because of the sand; and 3) it was too difficult to use, mainly because of the need for daily dosing, the large dose size, and the height of the filter.

Objective 2: Evaluate the impact of intermittent versus continuous operation on BSF performance.

Five laboratory BSF columns were operated with intermittent dosing while three were operated continuously. The BSF was initially designed to eliminate the cause of reduced microbial removal during intermittent operation of SSF, namely by preventing anoxic conditions from developing within the schmutzdecke, so that intermittent and continuous operation should theoretically be equivalent. However, the present study found that even with the design modifications between BSF and SSF, intermittent columns did still develop anoxic conditions within the schmutzdecke, and continuously operated filters performed significantly better than intermittent filters at removing *E. coli* (3.71 $\log_{10}$ vs. 1.67 $\log_{10}$), bacteriophage MS2 (2.25 $\log_{10}$ versus 0.85 $\log_{10}$), and turbidity (96% versus 87%).

Objective 3: Evaluate the impact of the multi-day residence periods on BSF performance.

Laboratory BSF columns were operated with one, two, and three day residence periods, with three replicates for each. Increasing the residence periods of BSF to two and three days did not lead to a reduction in filter performance in terms of *E. coli* removal rates. However, longer residence periods did lead to portions of the filter becoming anaerobic. Filtered water had lower DO in filters with longer residence periods, and lower nitrate, but higher nitrite concentrations and higher EC.

CHAPTER 8 Recommendations

Although one key reason that biosand filters were not appropriate for St. Cuthbert's was the cultural practice of householders spending long periods of time away from the home leading to filters stagnating or drying out, it is possible to address other concerns identified in that field study based on the results of the laboratory research.

- **Use a plastic filter box.** The plastic filter box is available in many parts of the world. The main disadvantages are that the plastic model is less durable and would need to be imported as opposed to the concrete model which was locally manufactured. However, the plastic filter boxes are considerably lighter and smaller than the concrete models. They may also appear more modern, and thus more trustworthy, to this cultural group who found the concrete models "primitive".
- **Reduce the filter height and volume**. The height of the filter was a challenge in this community. The 18 L dose volume needed to be lifted above waist height to pour into the filter, and many people stopped using the filter due to the physical difficulty of performing this task or due to back pain. The present research found that there was little advantage to filter media depths beyond 30 cm, and so the media column could be shortened without reducing filter performance. The reservoir volume would need to be proportionally reduced to ensure that each dose volume did not exceed the media pore volume.
- **Residence times of one to three days**. The required dosing frequency was intimidating to some households in this community and led to their abandoning the filter. Allowing for more flexibility in dosing frequency when instructing the households on filter operation may have increased acceptance of the technology. However, this is only applicable to communities where nitrogen levels in source water are not of concern.
- **Develop an effluent reservoir.** A key issue with the biosand filter as compared to ceramic candle filters and hypochlorite solution is

recontamination of treated water. The ceramic candle filters have a built in reservoir from which users can directly serve themselves, while hypochlorite solution offers residual chlorine which continues to protect water after treatment has occurred. In contrast, the biosand filter requires users to place a separate container under the spout of the filter to collect treated water. Both the container and the spout may become contaminated. A built-in effluent reservoir with a serving tap could solve this issue. Coating this reservoir with an antimicrobial product, such as colloidal silver, could provide continued protection from post-collection contamination, as well as improve virus removal. A second option would be to fit the BSF spout with a product which provides a low dose of chlorine to treated water as it enters the reservoir.

- **Investigate the impact of higher standing heads on BSF performance.** This would contribute to testing the initial theories justifying the modifications to SSF that first led to the BSF, but which have never been assessed. From a practical viewpoint, a deeper standing head would offer improved protection of the schmutzdecke during dosing.
- **Quantify the impact of temperature on BSF performance.** The results from the present research suggest that even a small temperature difference may have a significant impact on filter performance. This may contribute to explaining some part of the high variability noted in field settings. Also, although implementation of the BSF is widespread, most field studies of BSF have occurred in warm climates. Having a clearer understanding of the impact of temperature could assist in evaluating BSF appropriateness for temperate climates.
- **Investigate the impact of non-consistent use of BSF filters, including changing source water quality and changing residence periods.** In field settings surface water quality may change with seasons (i.e. wet versus dry season) and users may switch between rain, ground, and surface water sources. They also may use variable residence periods, due to natural variations in household water demand. Laboratory studies

typically use a consistent water source and residence period and it is possible that these practices reduce filter effectiveness.

- **Identify the microbial communities inhabiting BSF and contributing to pathogen removal.** The design of the filter could be improved by ensuring optimal conditions are met for the specific microbial species which are responsible for pathogen removal. This would also assist in identifying the environmental limitations of the technology, such as influent pH.
- **Engage community members in stakeholder engagement processes.** Future work in communities could be improved with alternative strategies for stakeholder engagement which better capture traditional knowledge and community preferences. Questionnaires can provide only a limited amount of information. Projects are more likely to succeed with stakeholder involvement.

CHAPTER 9 Contributions to knowledge

The research contained in this thesis led to the following original contributions to knowledge concerning biosand filtration:

1. *E. coli* and bacteriophage MS2 removal rates are significantly lower in biosand filters which are operated intermittently compared to those which are operated continuously.
2. *E. coli* removal rates are not significantly different between biosand filters operated with one, two, or three day residence periods.
3. There is no additional filtration benefit in terms of *E. coli* or MS2 removal to filter depths beyond 30 cm.
4. Hydraulic conductivity declines over time throughout the depth of the biosand filter, not only at the schmutzdecke.
5. Dissolved oxygen is consumed throughout the entire media column of the BSF during filtration, and during the residence period.

CHAPTER 10 References

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APPENDIX A

Photographs

Figure A-1 Standpipe S1 with water collection buckets

Figure A-2 Resident washing clothes at Korkobani Creek

Figure A-3 Typical drinking water storage bucket

Figure A-4 Biosand filter with safe water storage container

Figure A-5 Ceramic candle filter

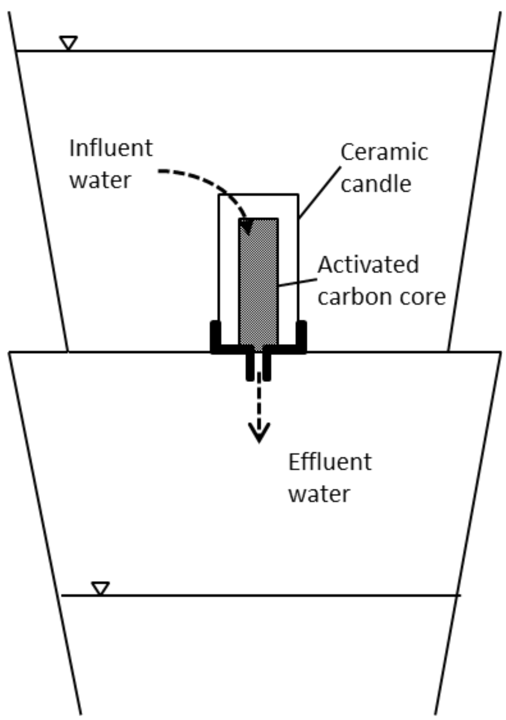

Figure A-6 Ceramic candle filter schematic

Figure A-7 Chlorosol with safe water storage container

Figure A-8 Columns in the laboratory

APPENDIX B

Questionnaires and surveys

RESEARCH CONSENT FORM

Title of Research: Development of Appropriate Point-of-Use Water Treatment Systems for Rural Amerindian Communities in Guyana

Researcher: Candice Young-Rojanschi, PhD. student, Bioresource Engineering

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Project Partners: Guyana Water Inc., CARIWIN (Caribbean Water Initiative), Guyana Ministry of Agriculture Hydrometeorological Service

I am a student at McGill University in Canada and I am studying about water and health, on a project supported by Guyana Water Inc. and CARIWIN with Guyana Ministry of Agriculture Hydrometeorological Service.

The purpose of this project is to learn about the water, hygiene and sanitation of people in Amerindian communities in Guyana.

I am here to ask you to participate in my study by answering some questions about your own household. If you choose to participate, I will ask you some questions about your household's knowledge and practices relating to water. Some of the questions are about demographics (like about how many people are in the house) and some are about health.

You won't have to answer any question that you don't feel comfortable with.

I would need your signature on this form to show that you agreed to be surveyed, but this consent form will be kept separate and your name won't be on the survey form itself and so that no one will know who answered the survey. The survey is completely CONFIDENTIAL.

Your signature below shows that you agree to participate in this study.

May I take a GPS reading of where your house so that I can calculate how far this household is from the river/tank/community taps/etc…? I will black out the measurement on the form once I have calculated the distance, so that no one else can see it or try to identify the house is from it.
☐ Yes ☐ No

I have read the above information and I agree to participate in this study

Signature: ___________________ Researcher's Signature:__________________________

Date: ______________________________

1) Questionnaire Number : ____________________________
2) Date: ____________________________
3) Interviewers: ____
4) Community: ____________________________
5) Location of house (GPS) ______________, ______________, elev ________

Health:

Please be as honest as possible. We're trying to understand the water situation for the community. Your name isn't on the questionnaire anywhere.

The World Health Organization defines diarrhoeal disease as the passing of 3 or more loose or liquid stools per day.

6) How many children in this household had diarrhoeal disease in the last 2 weeks?

Child #1	Child #2	Child #3	Child #4
Age: ____	Age: ____	Age: ____	Age: ____
Gender: ____	Gender: ____	Gender: ____	Gender: ____

7) How many adults in this household had diarrhoeal disease in the last 2 weeks?

Adult #1	Adult #2	Adult #3	Adult #4
Age: ____	Age: ____	Age: ____	Age: ____
Gender: ____	Gender: ____	Gender: ____	Gender: ____

8) In your opinion, to what extent is diarrhoeal disease a problem for adults in your community?

- ☐ Not really a problem
- ☐ Somewhat of a problem
- ☐ A big problem

Comments:

____

9) In your opinion, to what extent is diarrhoeal disease a problem for children in your community?

- ☐ Not really a problem
- ☐ Somewhat of a problem
- ☐ A big problem

Comments:

____

Water Sources:

10) Do you have a farm/garden?
    a) ☐ Yes☐No
    b) Is it ☐ near the house☐ somewhere else? How far? ________________________________
    c) Do you ever need to water the plants (e.g. in dry season)? ☐ Yes☐No
    d) Where do you get the water for that? ____
    e) How much water do you use to water plants, and how often? _____________________________
    f) Who is in charge of getting that water? Age __________ ☐ Male ☐ Female

11) Do you have a tap:

    ☐ in your house?
    ☐ in your yard?
    ☐ in your community?

12) Where do you usually get your water for:

	Wet Season	Dry Season
a) Drinking:	______________________	______________________
b) Cooking:	______________________	______________________
c) Washing wares:	______________________	______________________
d) Washing clothes:	______________________	______________________
e) Bathing (adult):	______________________	______________________
f) Bathing (childr:	______________________	______________________
g) Cleaning house:	______________________	______________________
h) Watering animals:	______________________	______________________
i) Other: ______	______________________	______________________

13) For each source:
    a) What is the source? (e.g. rainwater, tap, creek)
    b) GPS Location. If GPS is not available, then approximate distance (e.g. 1 km, half a mile, etc...)
    c) About how much water do you collect and use each day from this source?
    d) Who generally collects it? (Gender, Age) Do the children help collect it?
    e) About how much time does it take to go there, get the water, and come back?

	Source 1	Source 2	Source 3	Source 4
a) Source				
b) GPS or Distance				
c) How much?				
d) Who? Male/Female Age				
e) How long?				

14) Do children ever collect water? ☐Y ☐N ☐not applicable (*e.g. no children, children too young*)
   a) How often:
      - ☐ more than once per day
      - ☐ about once per day
      - ☐ more than once per week
      - ☐ about once per week
      - ☐ less often than every week
   b) Age ___________ ☐ Male ☐Female

15) Do men ever collect water? ☐Y ☐N ☐not applicable (*e.g. no man in the household*)
   How often:
      - ☐ more than once per day
      - ☐ about once per day
      - ☐ more than once per week
      - ☐ about once per week
      - ☐ less often than every week

16) Do women ever collect water? ☐Y ☐N ☐not applicable (*e.g. no woman in the household*)
   How often:
      - ☐ more than once per day
      - ☐ about once per day
      - ☐ more than once per week
      - ☐ about once per week
      - ☐ less often than every week

17) If rainwater is used, describe.

____

____

☐ Black tank ☐ Other

Is there a fabric or anything on the barrel to keep leaves, etc... off? ☐Y ☐N

____

18) When collecting water from a well, creek, or pond, what do you do to prevent leaves and dirt from mixing in? *(e.g. collect from moving water that looks clear, let it settle, try to take from below the surface, use a cloth to strain, etc...)*

____

19) Do you ever need to wait for other people in a line before it is your turn to collect water? ☐Y ☐N

20) Do you ever boil or treat your water before using it? ☐Y ☐N

a) When would you do this? *(e.g. for a sick person)*

____

b) When was the last time you did this?

____

c) What did you do to treat it?

____

21) Are there ever times when you not able to get drinking water from where you usually do? (e.g. pump is turned off for well or broken, rainwater tank is empty, etc...) If so, when was the last time that happened? What did you do?

____

____

22) Where do the children get drinking water from when they are at school?

____

23) Does anyone in the household work in the community but away from the household (e.g. farm, shop, etc...)? Do they get drinking water from somewhere when they are working? Where?

____

24) What are some other times when you need drinking water, but are not at home? Where do you get drinking water from then?

____

____

25) Do you ever pay for water? ☐Y ☐N

Explain:

____

____

26) How is water stored?

Quantity: ____

Covered ☐Y ☐N

☐ Tapor ☐ Scoop (if scoop, then scoop with what?) _______________

Comments:

____

How often do you clean the storage tanks? _______________________

27) How is drinking water stored?

Quantity: ____

Covered ☐Y ☐N

☐ Tapor ☐ Scoop

If scoop, then scoop with what? __________________________

Is the scoop only used for this purpose? ____________________

Does the scoop have a handle to prevent needing to touch the water? ☐Y ☐N

Comment on the scoop: _________________________________

Comments:

____

Hygiene and Sanitation

28) When do you usually wash your hands? (e.g. after toilet, after eating)

____

29) Do you use soap when washing your hands? ☐Y ☐N

When?

____

Observe handwashing facility and describe.

____

Is there soap available? ☐Y ☐N

30) Whose job is it to teach the children about hygiene? _____________________

31) What type of toilet facility is usually used by people in the household?

☐ Bush/none
☐ Pit Toilet → ☐ Slab ☐ No slab
☐ Toilet hanging over river
☐ VIP Latrine *(Ventilated Improved Pit Latrine)*
☐ Flush toilet → ☐ Piped Flush ☐ Pour Flush
→ ☐ Septic Field ☐ Sewerage Connection
☐ Other ____

32) If flush, then where do you get water from for flushing the toilet?

____

33) Is this toilet ☐ private or ☐ shared with other households?

How many households? ____________________

34) *Observe toilet facility and describe.*

____

Is the seat/toilet bowl clean and free from feces? ☐Y ☐N

35) What do you do about sanitation for babies who are too young to use the toilet? (*Where does the fecal matter go? Where are the diapers disposed of or washed? If in a rubbish bin, is there a lid for the bin?*)

____

____

36) Do you think your household sanitation option is:

a) Healthy? ☐Y ☐N

b) Gives enough privacy? ☐Y ☐N

c) Safe to use, even at night? ☐Y ☐N

37) Do you have any other comments to share about sanitation? Anything you don't like?

____

Household Information

38) Is the household an ☐ extended or ☐ nuclear *(husband, wife, kid*s) family?

a) Comment:

____

b) Are you ☐ married, ☐ single, or ☐ common-law

39) If married or common-law, is your partner mostly living in the ☐ household, ☐ away

40) Highest achieved schooling of adults in the household:

Male: ____________________

Female: ____________________

41) Household composition:

Age	# Male	# Female
< 5		
6-17		
18-49		
> 50		

42) Do you have electricity? ☐Y ☐N

☐ community grid
☐ private generator
☐ other ________________________

43) Does the household own:

Y N

☐ ☐ a television
☐ ☐ a bicycle
☐ ☐ a radio
☐ ☐ a stand-by generator
☐ ☐ a mobile phone
☐ ☐ a gas/kero stove

44) When was the last time you left the community to visit another city or village?

☐ never
☐ more than one year ago
☐ more than one month ago
☐ more than one week ago
☐ this week

45) What is the furthest place that you have travelled?

☐ another village in the region (name) _____________________
☐ Georgetown
☐ another region (name) __________________
☐ another country _______________________

Opinions

46) Are there things that happen that make diarrhoeal diseases happen more often in your household, such as different seasons, using a different water source, places you visit, food you eat, beverages etc?

____

____

____

47) Please rank the following in terms of what you think is the best source for drinking water, to what you think is less good. (1 is best)

__ Rain water
__ Community pipe (source: ____)
__ Shallow well
__ Moving river
__ Pond
__ Store-bought bottled
__Other ____

These are just questions about your opinions. It isn't a test, just a survey to see what people think. I'll read out a sentence, then you say whether you agree, disagree, or don't have on opinion.

	Agree	Disagree	No opinion
48) Flowing water is safe to drink.	☐	☐	☐
49) All children get diarrhoeal disease sometimes, it is a normal part of growing up.	☐	☐	☐
50) We get used to the black water; it is safe for us to drink.	☐	☐	☐
51) I know someone who died or lost a child because of diarrhoeal disease.	☐	☐	☐
52) Still water in a pond is safe to drink.	☐	☐	☐
53) There are some things in the river that make it not safe to drink.	☐	☐	☐

54) What do you think about people who won't drink the black water (from creek or river)?

____

____

55) When do you drink the black water (e.g. all the time, when in the forest, when washing at the river)?

____

____

56) In your opinion, what are the main causes of diarrhoeal diseases and what are the best ways to prevent it?

____

____

____

57) In general, whose job do you think it is to make sure that families have enough clean drinking water?
- ☐ men
- ☐ women
- ☐ neither/both, not a matter of gender

58) In general, whose job do you think it is to make sure the children know about good hygiene?
- ☐ men
- ☐ women
- ☐ neither/both, not a matter of gender

59) In your opinion, what do you think is the biggest water-related problem in your community?

____

60) In your opinion, what do you think is the biggest water-related problem you face at home?

____

Notes:

61) Participant sex: ☐M ☐F

62) Approximate age of participant (ask if the opportunity arises): ____________

☐ 18-50 ☐>50

63) Roofing material ☐ Zinc ☐ Thatch ☐ Other __________

64) House Type ☐ Raised ☐ Ground Level

☐ Wood Walls ☐ Concrete ☐ Other __________

☐ Painted ☐ Not painted/paint is peeled away

65) Additional Comments:

____

____

____

____

____

____

RESEARCH CONSENT FORM

Title of Research: Development of Appropriate Point-of-Use Water Treatment Systems for Rural Amerindian Communities in Guyana

Researcher: Candice Young-Rojanschi, PhD. student, Bioresource Engineering

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Project Partners: Guyana Water Inc. (GWI), CARIWIN (Caribbean Water Initiative), Guyana Ministry of Agriculture Hydrometeorological Service

This research project is to learn about which types of household level water treatment interventions work best and that people in St. Cuthbert's Mission like. In other countries these treatments have been found to purify water and reduce diarrhoeal disease. The results will help organizations like GWI plan interventions in Guyana.

Volunteers for this study will be asked to answer some questions about their household on a questionnaire, mark down on a chart the times when someone in the household has diarrhoeal disease, and agree to have the water in their house tested. In the last weeks of February, some households will be randomly selected by having their name drawn from a hat to receive a different water treatment intervention, while some households will not. After 1 month, and then again after 1 year, all the households will have their water tested again. The households that receive a treatment will also be asked a questionnaire about what their opinion is about the treatment.

The good thing about using a treatment to purify your water is that your household will be at less risk for waterborne sicknesses, like diarrhoeal disease. There are no anticipated risks.

There is no cost for participating in the study; the treatments will be free to the households that are selected. Not every household in the study will receive a treatment. There is no payment or salary for participating in the study.

This study is voluntary. That means that you don't need to participate if you don't want to. You can ask any questions you like whenever you like, and change your mind and stop participating in the study if you don't want to participate any more.

Your house will have a number assigned to it, so that the answers you give about your family's health won't have your name on it. They will be confidential.

You will be given a copy of this form to keep.

The study has been explained to me and my questions have been answered to my satisfaction. I agree to participate in this study.

Signature:______________ Witness: __________________ Date: _____________

1. Name ____
2. Neighbourhood ____
3. Do you usually have current/light (Y or N)? ________
4. Is your household a nuclear household (meaning father, mother, and children), or is it an extended household with grandparents and grandchildren or aunts and uncles? Circle the answer.
   a. Nuclear
   b. Extended

5. Household composition:

Age	# Male	# Female
< 5		
6-17		
18-49		
> 50		

6. What is the main source of drinking water for your household? Please be specific about which creek, pipe, etc.
   a. Wet season: _________________________________
   b. Dry season: __________________________________

7. What type of drinking water storage is mainly used?
   c. 5 gallon bucket with lid, cup for a scoop
   d. 2 gallon bucket with lid, cup for a scoop
   e. 5 gallon jar
   f. Other: _______________________________________
8. What type of toilet do you have? Circle the answer
   g. None – use the bush
   h. Pour flush toilet
   i. Piped flush toilet
   j. Pit latrine, no seat
   k. Pit latrine, with toilet seat
   l. Other (describe) ____

The World Health Organization defines diarrhoeal disease as the passing of 3 or more loose or liquid stools per day.

Note: This is likely a more mild definition than you may use (e.g. it is not necessary to be severe enough to visit the health clinic).

Please keep this next sheet, and fill it out over the next weeks according to the WHO definition.

The World Health Organization defines diarrhoeal disease as the passing of 3 or more loose or liquid stools per day. Please record in the spaces below any diarrhoeal disease in your household over the next weeks. Include whether it is a male or female (M or F) and their age. For example, a 50 year old man would be M50.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
08-Feb	09-Feb	10-Feb	11-Feb	12-Feb	13-Feb	14-Feb
15-Feb	16-Feb	17-Feb	18-Feb	19-Feb	20-Feb	21-Feb
22-Feb	23-Feb	24-Feb	25-Feb	26-Feb	27-Feb	28-Feb
01-Mar	02-Mar	03-Mar	04-Mar	05-Mar	06-Mar	07-Mar
08-Mar	09-Mar	10-Mar	11-Mar	12-Mar	13-Mar	14-Mar
15-Mar	16-Mar	17-Mar	18-Mar	19-Mar	20-Mar	21-Mar
22-Mar	23-Mar	24-Mar	25-Mar	26-Mar	27-Mar	28-Mar

ONE MONTH QUESTIONNAIRE

Thank you for participating in the water study! These next questions are to get your opinions on the water treatment that you have been testing for the last month.

1) Does this household still use the treatment?
    a. Still uses treatment
    b. No longer uses treatment
        i. Household has moved
        ii. Treatment is broken
        iii. Just don't like it
        iv. Why? ____
2) What did you use the treated water for?
    a. Just drinking
    b. Just cooking
    c. Cooking and drinking
    d. Other: ____
3) Over the last month we used the treatment for drinking water:
    a. All of the time
    b. Most of the time (75%)
    c. Some of the time (50%)
    d. Now and then (25%)
    e. Not very much
4) How often did you treat the water?
    a. More than once a day
    b. About once a day
    c. About every two days
    d. Once a week
    e. Less than once a week
5) What is your overall opinion of the water treatment?
    a. Very good
    b. Good
    c. Just okay
    d. Not good
    e. Very bad
6) How often do you plan to use the treatment next month?
    a. All of the time
    b. Most of the time
    c. Some of the time
    d. Now and then
    e. Not very much

Water Quality Measurements

Household #: ______________
Treatment Group:___________
Date: _____________________
Time: ____________________
Source of Sample: __________
________ C
________ TDS g/L
________ pH
________ NTU
________ Coliform Colonies
________ mL Sample size

7) Do you think the treated water has a different temperature than non-treated water?
   a. Much colder
   b. A little colder
   c. Haven't noticed a difference
   d. A little warmer
   e. Much warmer
8) Do you think the treated water has a different taste than non-treated water?
   a. Much better
   b. A little better
   c. Haven't noticed a difference
   d. A little worse
   e. Much worse
9) Do you think the treated water has a different smell than non-treated water?
   a. Much better
   b. A little better
   c. Haven't noticed a difference
   d. A little worse
   e. Much worse
10) Do you think the treated water looks different than non-treated water? (colour, clear vs. cloudy, etc...):
   a. Much better
   b. A little better
   c. Haven't noticed a difference
   d. A little worse
   e. Much worse
11) Do you think that using the treated water has affected your family's health?
   a. Much better
   b. A little better
   c. Haven't noticed a difference
   d. A little worse
   e. Much worse
12) Do you think maintaining the equipment (e.g. cleaning the container or filter) was easy, or too complicated?
   a. Easy
   b. In the middle
   c. Too complicated
13) Do you think using the equipment was easy to use, or too complicated?
   a. Easy
   b. In the middle
   c. Too complicated
14) Do you think the equipment treats enough water?

a. More than enough water for the household
b. Just barely enough for the household
c. Not enough for the household

15) Do you think the equipment was fast enough, or too slow?
    a. Fast enough
    b. Somewhat slow
    c. Too slow
16) Do you think the equipment takes up too much space?
    a. Yes
    b. Haven't really noticed/In the middle
    c. No

Do you think the equipment is nice looking, or ugly?

d. Ugly
e. Haven't really noticed/In the middle
f. Nice looking

17) Who in the family was mostly in charge of treating the water?
    a. Age ________ b. Gender: M / F
18) Who in the household was mostly in charge of maintaining the equipment?
    a. Age ________ b. Gender: M / F
19) Comments: ____
20) Person answering survey:
    a. Age ________ b. Gender: M / F
21) Has anyone in this household experienced diarrhoeal disease, that being the passing of 3 or more loose or liquid stools in one day, in the last week? If so, what is their age and gender? ____
22) Which of the following does this household own:
    a. Circle all that apply:

Fridge/Freezer	Television	Vehicle	Motorcycle	Black	Tank
Cell phone	Working radio	Shop			

    b. Type of roof: zinc thatch other _________________________________
    c. Primary type of stove: gas kero wood other _________________
    d. Number of rooms in the household used for sleeping: ______________________

ONE-YEAR QUESTIONNAIRE

This is the last questionnaire and sample you'll be asked for in the water study. Thank you for your participation and support up to now!

TREATMENT GROUPS

1) What do you think is the best thing about the (Chlorosol or filter)?

____

2) What do you think is the worst thing about the (Chlorosol or filter)?

____

3) What do you think could be changed to make the (Chlorosol or filter) better?

____

4) Does this household still use the (Chlorosol or filter)?
   a. Still uses the treatment
      i. Why? ____
      ____
      ii. Use the storage container? Y / N
   b. Used to use the treatment, but stopped
      i. Why? ____
      ____
      ii. Use the storage container? Y / N
   c. Never used the treatment
      i. Why? ____
      ____
      ii. Use the storage container? Y / N (After Q 2-4, go to Q24)
5) What did you use the treated water for?
   a. Just for when kids were sick
   b. Drinking
   c. Cooking, preparing food, washing vegetables
   d. Both drinking and cooking
   e. Other: ______________________________
6) When you use the treated water for drinking water, who in the household used it? (Circle all that apply)
   a. Babies (age 1 & 2)
   b. Children under 5 years old (age 3 & 4)
   c. Children 5 years old and older
   d. Adults (mother, father, grandparents)
7) Over the last month we used the treatment for drinking water:
   ☺☺ Usually
   ☺ Frequently (75%)
   😐 Half the time
   ☹ Occasionally (25%)
   ☹☹ Rarely

8) How often did you treat water with the Chlorosol/filter? (e.g. five times a day? Every 5 days?) ____

9) Did you treat: Rain water? □ Y □N □ n/a
Pipe water? □ Y □N □ n/a
Creek water? □ Y □N □ n/a

10) What is your **overall** opinion of the water treatment?
☹☹ Really didn't like
☹ Didn't like
😐 In the middle
☺ Liked
☺☺ Really liked

11) How often do you **plan** to use the treatment next month?
☺☺ Usually
☺ Frequently (75%)
😐 Half the time
☹ Occasionally (25%)
☹☹ Rarely

12) Do you think the treated water has a different **temperature** than non-treated water?
☹☹ Hot
☹ A little warm
😐 No difference
☺ A little cooler
☺☺ Cold

13) Do you think the treated water has a different **taste** than non-treated water?
☺☺ Much better
☺ A little better
😐 Alright
😐 No difference
☹ A little worse
☹☹ Much worse

14) Do you think the treated water has a different **smell** than non-treated water?
☺☺ Much better
☺ A little better
😐 Alright
😐 No difference
☹ A little worse
☹☹ Much worse

15) Do you think the treated water **looks** different from non-treated water? (colour, cloudiness, etc...
☺☺ Much better
☺ A little better
😐 Alright
😐 No difference
☹ A little worse
☹☹ Much worse

16) Do you think that using the treated water has affected your family's **health**?
☺☺ Much better
☺ A little better
😐 Alright
😐 No difference
☹ A little worse

☹☹ Much worse

17) Do you think **maintaining** (e.g. cleaning the container or filter) the (Chlorosol or filter) was:
   - ☺ Easy
   - 😐 In the middle
   - ☹ Too complicated

18) Do you think **using** the (Chlorosol or filter) was:
   - ☺ Easy
   - 😐 In the middle
   - ☹ Too complicated

19) Do you think the (Chlorosol or filter) treats **enough** water?
   - ☺ More than enough for the household
   - 😐 Just barely enough
   - ☹ Not enough for the household

20) Do you think the (Chlorosol or filter) was**:**
   - ☺ Fast enough
   - 😐 In the middle
   - ☹ Too slow

21) Do you think the (Chlorosol or filter) takes up too much **space**?
   - ☹ Yes
   - 😐 In the middle
   - ☺ No

22) Do you think the (Chlorosol or filter) is:
   - ☺ Nice looking
   - 😐 In the middle
   - ☹ Ugly

23) Who in the family was mostly in charge of:
   a. treating the water? Age _______ M / F
   b. maintaining the (Chlorosol or filter)? Age _______ M / F

ALL HOUSEHOLDS (TREATMENT GROUPS + CONTROL)

Household # ______________________
Treatment Group: __________________

24) From what you've seen in the community, please rank the treatments in the study, where 1 is the best and 4 is the worst, in your opinion:
    ___ Chlorosol
    ___ Ceramic bucket filter
    ___ Concrete Biosand filter
    ___ No treatment
    Why? ____

25) In the last week, has anyone in this household experienced diarrhoeal disease, that being the passing of 3 or more loose or liquid stools in one day? Y/N If Y, then Age ________ M / F

26) Person answering survey: Age ________ M / F

27) Are there any changes in the household composition since the last visit? (See attached previous survey) ____

28) Can you please show me where you usually wash your hands? *If no soap is visible, ask if they have any as some people keep it inside to protect from rain*
    Soap ☐ at handwashing site ☐ inside/other location ☐ no soap
    Notes: ____

29) Additional Comments: ____

Water Quality Measurements

Date: _____________________________ _____________ °C

Time: _____________________________ _____________ TDS g/L

Water source: _______________________ _____________ DO

Treatment: _________________________ _____________ pH

Storage Container: ___________________ _____________ NTU # 1

☐ Pour ☐ Tap ☐ Scoop _____________ _____________ NTU # 2

How many days ago was the water collected? ___________ __________ mg/L Free Chlorine

__________ mg/L Total Chlorine

Sample 1	Sample 2	Sample 3
_______Coliform Colonies	_______ Coliform Colonies	________ Coliform Colonies
______ mL Sample size	________ mL Sample size	________ mL Sample size

THANK YOU FOR PARTICIPATING IN THE WATER STUDY! YOUR PATIENCE AND CONTRIBUTION HAVE BEEN VERY HELPFUL AND ARE VERY MUCH APPRECIATED.