Modeling the Complexities of Water, Hygiene and Health in Limpopo, South Africa

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Abstract

Poor household drinking water quality and the early childhood diarrhea (ECD) and child growth stunting that result from it are a scourge that leads to the premature death of nearly 1.6 million children worldwide each year. Researchers have long studied the causes and prevention strategies of poor household water quality and ECD using intervention-control trials. Although the results of such trials can lead to useful information, they do not capture the complexity of this human/engineered/natural system. This dissertation reports on the development of an agent-based model (ABM) to study such a system in Limpopo, South Africa. This method proved to be an effective tool to develop a robust, quantitative understanding of the *complex* coliform bacteria transmission chain that leads to ECD and to investigate key mechanisms, risk factors, behaviors and intervention strategies to mitigate such transmission. This was achieved in three main parts. The first was an investigation of the sources and regrowth mechanisms of coliform bacteria as well as water, sanitation and hygiene (WASH) behavior in the communities. The second part was to use that information to inform the development of an ABM and use that ABM to explore the various risk factors affecting the outcome variables of household water quality, ECD incidences and child growth stunting. Lastly, the ABM was used understand the long-term sustainability of a ceramic water filter (CWF) campaign using field data about longitudinal microbial effectiveness.

In addition to these three main studies related to the ABM, data from a fourth study was analyzed which investigated the possible use of a silver-infused torus which has the potential to reduce biological contamination and regrowth in the lower reservoir of CWFs and compared the long-term effectiveness of such filters to point-of-use (POU) chlorination and CWFs without the toruses.

The first studied related to the ABM comprehensively investigated contamination sources and the biological and chemical mechanisms sustaining them in two adjacent communities in rural Limpopo, South Africa. The eight month study was conducted of household and source water quality measurements, measurements of biofilm layers on the inside of household water storage containers and water transfer devices, and measurements of hand-based coliforms and hand-washing effectiveness. A 7-day water container incubation experiment was also performed to determine the biological and chemical changes that occur in a household water storage container independent of human interference. Results indicate that household drinking water frequently becomes contaminated after collection but before consumption (197 vs 1046 CFU/100 mL, $n = 266$, $p < 0.001$). The most important contamination sources include biofilm layers on the inside of storage containers (1979 CFU/100mL), hands (1041 CFU/100

mL) and coliform regrowth resulting from high assimilable organic carbon (AOC) levels during storage. A maximum specific growth rate, μ_{max}, of 0.072 h^{-1} was measured for total coliform bacteria on AOC and a high correlation between AOC concentrations and the growth potential of total coliform bacteria was observed. These results support the implementation of point-of-use water treatment and other interventions aimed at maintaining the safe water chain and preventing biological regrowth.

The second study captured the essential WASH elements of the communities and their water contamination chain as identified in the first study to construct the ABM. An extensive analysis of those elements explored behaviors including water collection and treatment frequency as well as biofilm buildup in water storage containers, source water quality, and water container types. Results indicate that interventions must be optimally implemented in order to see significant reductions in ECD. Household boiling frequency, source water quality, water container type and the biofilm layer contribution were deemed to have significant impacts on ECD. Furthermore, concurrently implemented highly effective interventions were shown to reduce diarrhea rates to very low levels even when other, less important practices were sub-optimal. This technique can be used by a variety of stakeholders when designing interventions to reduce ECD incidences in similar settings.

The third study used the ABM to investigate CWFs. CWFs are a point-of-use water treatment technology that has shown promise in preventing ECD in resource limited settings. Despite this promise, some researchers have questioned their ability to reduce ECD incidences over the long term since most effectiveness trials conducted to date suffer from lack of blinding and are thus potentially biased. This study uses the ABM to explore factors related to the long-term sustainability of CWFs in preventing ECD and was based on a three year longitudinal study of microbial effectiveness, usage and willingness-to-pay (WTP) for replacement filters. Specifically, filter prevalence, usage, breakage rates and dates, microbial effectiveness, filter cleaning and linear usage declines were explored. There were additional investigations about WTP for new filters and user perceptions of water quality. This study demonstrated the ability and flexibility of the ABM to simulate interventions. Results indicate that human behaviors are the primary driver of the outcome metrics and that deteriorating filter effectiveness has a significantly negative role on those same outcome metrics. In fact, microbial effectiveness declines to such an extent as to make the CWFs practically useless, on average, at preventing ECD after 3 years. Overall, the model predicts that a ceramic filter intervention can reduce ECD incidence by 41.3%. The three most important factors included CWF usage, prevalence and linear usage declines. It was also shown that CWF log reduction values less than 3 resulted in sub-optimal outcomes and that users should clean their filter at least once every six months to improve outcomes. Finally, this study showed that outcome variables could be improved somewhat if replacement filters were available for 100 South African Rand or less and if community members recognize and treat their water more frequently when water quality is worse than 10 CFU/100mL of total coliform bacteria. In summary, the CWF can be a highly effective tool in the fight against ECD, but every effort should be made by implementing agencies to ensure consistent use and cleaning.

The fourth study concurrently compared three different POU technologies including POU chlorination, CWFs and CWFs plus lower reservoir toruses to prevent biological contamination and regrowth. These results indicate that all three technologies decline in microbial removal efficiency over time, but there is no clear difference between the three technologies. The relative equity was likely caused by the fact that the torus, as designed, was unable to maintain silver concentrations in the lower reservoir water at levels significantly higher than CWFs without the toruses. Furthermore, although chlorination did prove to be effective at reducing total coliform and *E. coli* levels, it suffered from poor adherence. These results are consistent with the other studies reported on in this dissertation in that they highlight the relative importance of compliance and human behaviors as playing a large role in ECD reduction.

The three ABM studies demonstrate the usefulness of systems approaches to investigate the complex coliform transmission chain from source to consumption and to identify risk factors and behaviors that can mitigate the scourge of contaminated water leading to ECD in resource-limited settings. The fourth study adds to it by re-emphasizing the importance of human behaviors in ECD prevention. Collectively, this dissertation has attempted to develop a robust, quantitative understanding of the *complex* coliform bacteria transmission chain that leads to ECD and it investigates key mechanisms, risk factors, behaviors and intervention strategies to mitigate such transmission.

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In addition to the UVA faculty and staff, there were a number of other researchers who helped this work tremendously. Rachel Hensley from UVA Wise was a tremendous help to me in the field data collection in South Africa. Dr. Samie Amidou allowed us to use his laboratory space at Univen and introduced us to his students Mashau Funanai, Ntekele Phindile and Mary Ramantswana who conducted the membrane filtration experiments. Professor Vhonani Netshandama graciously helped us organize Univen student participation and served as a valuable conduit between us and the communities. Her students Kwathiso Netshifhefhe and Elly Mbonei collected field data month after month and were invaluable partners in our community field work. In addition, Univen students Khuthalani Mathoma, Nkuna Patrick, Nkgapela Rosinah and Muvhango Kimmie helped quite a bit with our field work.

I would like to thank my parents who always inspired me to never stop learning, to passionately care about the lives of the less fortunate and do my best to make their lives a little better.

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Abbreviations

- ABM - Agent-Based Model
- ECD - Early Childhood Diarrhea
- HAZ_2 - Height for Age Z-Score at age 2
- WASH - Water, Sanitation and Hygiene
- WQ_i - Daily water quality of the i^{th} household
- CWF - Ceramic Water Filter
- MT - Municipal Tap
- CP - Community Piped
- SW - Surface Water
- POU - Point-of-Use

CHAPTER 1

Introduction

Access to sustainable water and sanitation (WASH) facilities is one of the biggest challenges the developing world faces as an increasing number of people inhabit those areas. More than 1.1 billion people in the world lack access to improved water sources and there are 2.6 billion who do not have adequate sanitation facilities. The United Nations estimates that 1.6 million children under five years of age die each year as a result poor access to WASH facilities (WHO, 2006). Early childhood diarrhea (ECD) is a major cause of these deaths which can also lead to serious problems such as stunting (Checkley *et al.* , 2008), long-term cognitive deficits (Niehaus *et al.* , 2002) and lower performance in school (Lorntz *et al.* , 2006). Finally, poor access to water and sanitation technologies disproportionally affects women and children who are primarily in charge of water resources in most developing nations.

Despite the fact that interventions strategies such as point-of-use water treatments and community source protection are thought to prevent ECD, most previous researchers have used intervention-control trials to measure before and after diarrhea rates. These trials fail to capture the *complex* water chain and do not take into account the human behavior that is critical to understanding how to prevent ECD. This dissertation will develop a novel means of understanding this complex system using an agent-based model (ABM).

1.1 Dissertation Goal and Outline

The causes of and prevention strategies for the coliform bacteria transmission that leads to ECD are numerous and complex. Therefore, the goal of this research was as follows:

> To develop a robust, quantitative understanding of the *complex* coliform bacteria transmission chain that leads to ECD and to investigate key mechanisms, risk factors, behaviors and intervention strategies to mitigate such transmission.

This dissertation goes beyond previous studies through its ability to model the *complex* human/engineered/natural pathogen transmission chain using an ABM informed by field data. This work was carried out in three parts which are discussed at length in Chapters 2, 3 and 4. Chapter 2 describes a field data collection effort designed and directed by the author in the communities about sources and regrowth mechanisms of coliform bacteria to inform the development of the model. Chapter 3 describes the development and behavior space analysis of that model. Chapter 4 describes the application of the model to understand a realistic ceramic water filter (CWF) campaign and is based on a field data collection effort led by L. Abebe and B. Ehdaie.

Complementing the work on the ABM was a fourth study described in Chapter 5. That study was conducted in 2009-2010 by E. Kallman and V. Oyanedel-Craver and was intended to compare the long-term performance of three point-of-use (POU) water treatment technologies. The three technologies include POU chlorination, CWFs and CWFs that include a silver-infused ceramic torus in the lower reservoir. This torus is designed to prevent biological contamination and regrowth in the lower reservoir. The author of this dissertation had no role in the design or implementation of that project, but the author did conduct all of the data analysis and is writing the manuscript for publication.

1.2 Publications and Presentations

This work will ultimately result in five peer-reviewed publications and three conference presentations. Chapter 2 was accepted for publication in the Journal of Environmental Engineering. Chapter 3, was recently published in Environmental Science and Technology. Chapter 4 will form the basis for the third paper which is being finalized with L. Abebe and B. Ehdaie. It will be submitted early this summer. The fourth paper based on Chapter 5 is likewise being prepared for submission and will likewise be submitted in the early summer. Finally, the author of this dissertation is a co-author on a fifth paper written by G. Learmonth and S. Pagsuyoin based on the original ABM that was coded by J. Demarest. Although this author made substantive intellectual contributions to that work, it will not be discussed in this dissertation.

- **Chapter 2:** Mellor, J. E., Smith, J. A., Samie, A., and Dillingham, R. A. "Coliform Sources and Mechanisms for Regrowth in Household Drinking Water in Limpopo, South Africa." Journal of Environmental Engineering. In Press.
- **Chapter 3:** Mellor, J. E., Smith, J. A., Learmonth, G. P., Netshandama, V. O., and Dillingham, R. A. (2012). "Modeling the complexities of water, hygiene, and health in Limpopo Province, South Africa." Environmental Science

Technology, 46(24), 13512 - 13520.

- **Chapter 4:** Mellor, J.E., Abebe, L., Ehdaie, B., Smith, J.A., Dillingham, R.A. (2013).“Modeling the Sustainability of a Ceramic Filter Intervention in Limpopo Province, South Africa”, In Preparation.
- **Chapter 5:** Kallman, E.N., Oyanedel-Craver, V.A., Mellor, J.E., Smith, J.A. (2013).“A Comparison of Three Point-of-Use Water Treatment Technologies”, In Preparation.
- Demarest, J.B., Pagsuyoin, S.A., Learmonth G.P., Mellor, J.E., Dillingham, R.A. (2013). “Development of a Spatial and Temporal Agent-based Model for Studying Water and Health Relationships: the Case Study of Two Villages in Limpopo, South Africa” Journal of Artificial Societies and Social Simulation. In Press.

In addition, this work has been presented at the following three conferences:

- **Chapter 3:** Mellor, J.E., Smith, J.A., Learmonth, G.P., Netshandama, V.O., Dillingham, R.A., (2012), “Modeling the Complexities of Water and Hygiene in Limpopo Province South Africa”, Abstract H21E-1220 presented at 2012 Fall Meeting, AGU, San Francisco, CA, 3-7 Dec.
- **Chapter 2:** Mellor, J.E., Smith, J.A., Dillingham, R.A.,(2012), “Pathogen Sources and Mechanisms for Regrowth in Household Drinking Water in Limpopo, South Africa”, Presentation Number LB-185 presented at the American Society of Tropical Medicine and Hygiene Annual Meeting, Atlanta, GA, 11-15 Nov.
- **Chapter 3:** Mellor, J.E. (2012), “Modeling the Complexities of Water, Hygiene and Sanitation in Limpopo Province South Africa”, presented at Water and Health Conference: Science, Policy and Innovation, University of North Carolina at Chapel Hill, Chapel Hill, NC, 29 Oct - 2 Nov.

1.3 Background

1.3.1 Causes and Prevention Strategies of ECD

The causes of and the solutions for ECD are complicated by the fact that there are a variety of transmission routes that are commonly thought to be important in the fight against diarrheal disease (Eisenberg *et al.* , 2007). These transmission routes are commonly summarized in the F-Diagram shown in Figure 1.1. That diagram highlights the pathways whereby human or animal feces can be transmitted to people through fluids (i.e. water), fields, flies (Emerson *et al.* , 1999), fingers (Curtis & Cairncross, 2003) and foods. Transmission can be stopped through the introduction of different technologies or practices such as increasing the practice of hand washing. Although it is clear that all of these vectors can contribute to the transmission of harmful pathogens, it is unclear which pathways dominate and which intervention strategies are most effective.

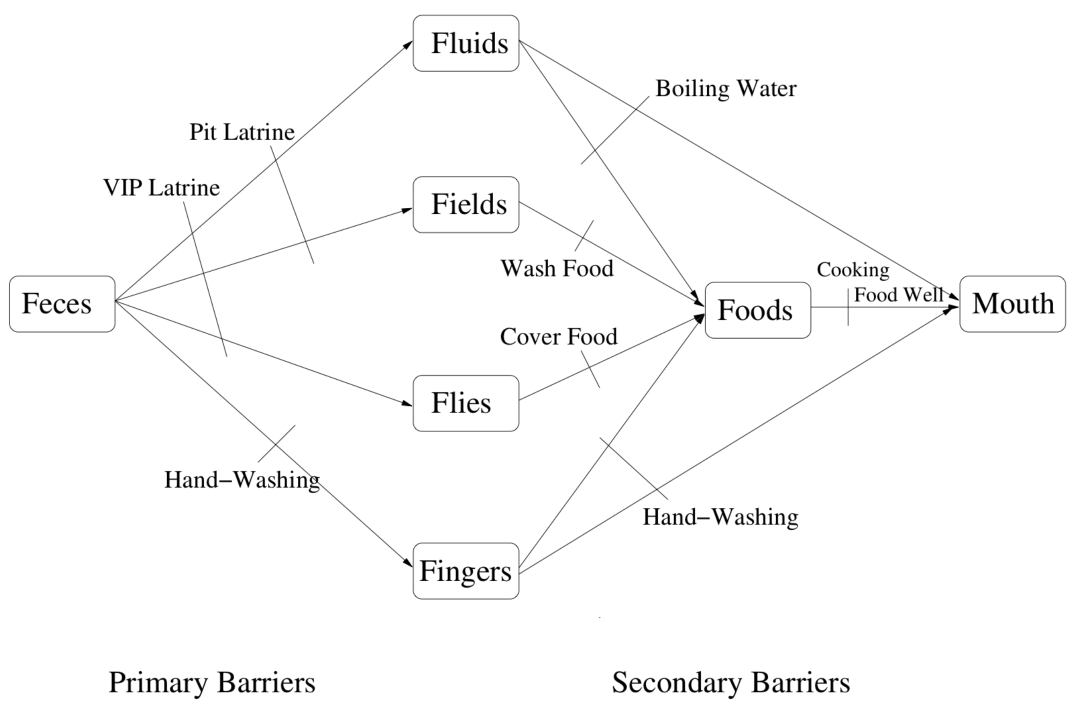

Figure 1.1: *The F-diagram showing the basic mechanisms by which feces from one individual or animal, passes through the environment, and into the mouth of another. Barriers that inhibit this process can be classified as primary and secondary barriers. Adapted from (Curtis* et al. *, 2000).*

Corroborating this complexity, a number of studies have concluded that water is frequently recontaminated through hand-contact (Roberts *et al.* , 2001) or that point of use water treatment devices are effective at reducing waterborne transmission

(Schmidt & Cairncross, 2009). Another report used biological reasoning to suggest that primary barriers such as safe stool disposal are more important than secondary barriers like hand washing (Curtis *et al.* , 2000). Two major meta-analyses found that hygiene, sanitation and household water treatment devices were more effective than community water source protection (Fewtrell *et al.* , 2005; Clasen *et al.* , 2007). Finally, research conducted in Uganda found that both multiple intervention strategies and household water treatment were highly effective means of reducing ECD (Mellor *et al.* , 2013c). This is because multiple intervention strategies can target multiple transmission pathways while household water treatment devices purify water just before consumption.

The heterogeneity of the literature as to which interventions strategies might work best is due largely to differences in design, follow-up and measures of outcomes. Therefore, comprehensive studies would need longer follow-up, better outcome measures and attention to socio-behavioral aspects like affordability and acceptability. In addition, they would need to address programmatic issues of sustainability and scalability as well as cost-effectiveness analyses. Doing studies like this would require a significant amount of time and resources while likely still failing to capture the complexities of pathogen transmission. A novel method to understand such systems is to use an ABM.

1.3.2 Agent-Based Modeling

Traditionally, scientists have taken a reductionist view of scientific phenomena: that is they look at systems hierarchically. However, this has led to a disparate and compartmentalized scientific view of the world that is not well suited to solving multidisciplinary problems (An, 2009). ABM is an object-oriented, spatial computer modeling technique used by researchers in fields as diverse as physics, economics, biology, medicine, ecology, finance, etc. to study complex systems. Complex systems have no central or coordinating mechanism therefore system-level behaviors cannot be predicted based on the knowledge of the individual components. Therefore, such systems may exhibit *emergent* behavior. The emergent behavior can be counter-intuitive and lead to valuable information that would have been difficult to measure using more traditional modeling techniques.

An agent-based model allows the user to "see the consequences of a particular hypothesis on a structure/conceptual model" because the static hierarchical model is now "a dynamic model in which the mechanistic consequences of each hypothesis can be observed and evaluated" (An, 2009). ABM is a stochastic form of modeling that deals with this issue through its agents who are given probabilities for different behaviors. When the program is run with its agents in parallel, the individual behavior probabilities collapse during each step of the run and population behavioral outputs are generated (An, 2009).

Public health experts are increasingly utilizing agent-based models to simulate the spread of diseases and the effectiveness of prevention strategies. Shi *et al.* (2010) used a spatial ABM to simulate the spread of the H1N1 influenza in the state of Georgia. Another study investigated the use of insecticide-treated mosquito nets in the prevention of malaria (Gu & Novak, 2009).

Agent-based modeling has also been used to study social consciousness and preferences (Chu *et al.* , 2009), community decision-making (Altaweel *et al.* , 2010), person-to-person diarrhea transmission (Bates *et al.* , 2007) and knowledge diffusion (Tawfik

& Farag, 2008). Agent-based models can simulate complex social phenomena such as fear of a disease (Epstein *et al.* , 2008). They can go beyond traditional epidemic models by simulating the direct contact of individuals who can adapt their behaviors rationally or irrationally according to disease prevalence (Epstein, 2009). Finally, their ease of use and highly visual nature makes them ideal tools for participatory modeling by a variety of stakeholders (Epstein, 2009).

Therefore, ABMs are an ideal tool to garner highly relevant and interesting information that can guide public health experts to focus their efforts at combating diarrheal disease in developing countries.

1.3.3 WHIL Project

This ABM work was part of the ongoing WHIL Project done in collaboration with the University of Venda (Univen), located in Limpopo Province, South Africa. It is being conducted in the nearby communities of Tshapasha and Tshibvumo.

Limpopo Province is South Africa's second poorest and most rural province (87% of its people live in rural areas). 16.2% of those tested were HIV positive in 2007/2008. Diarrhea is the second leading cause of death amongst children under four years of age (Bradshaw *et al.* , 2000). In addition, diarrhea rates are 1.7 times higher than the national average and have increased 170% between 2003 and 2008 in Vhembe District (Sello, 2010).

Some data was already collected for the WHIL project prior to this author's involvement that informed the early development of the model. That data came from a complete community census and community mapping project completed in 2009, the ceramic water factory feasibility study done in 2010, the on-going Mal-ED project and a point-of-use water treatment study completed by L. Abebe in 2010.

Some relevant highlights of that data are as follows. Tshapasha and Tshibvumo have about 3,000 residents that live in more than 400 households. Sanitation coverage is insufficient with only 200 latrines between the two communities. In Tshapasha, more people (80%) get their water from hoses entering their homes carrying surface water from a river uphill than they do from either municipal taps (MT) (12%) or surface water (SW) (6%). The hose water supply currently passes through one of two large storage tanks and can be chlorinated. Hereafter this water source will be called CP water. In Tshibvumo, 33% reported using MT as their primary source, while 39% got their water from CP and 24% from SW.

Both the CP and MT systems are prone to frequent outages in which case most households (62%, $n = 272$) have to rely on surface water from a polluted stream or from water that is stored for long periods. The average household in the communities keeps their water for 2.4 ± 0.4 days ($n = 150$). The surface water contamination is likely because the headwaters of the main water source for the two communities is in an agricultural area that is frequently grazed by cattle.

These factors make Tshapasha and Tshibvumo ideal communities to study the complexities of ECD in resource limited settings. Furthermore, the lessons learned from these studies is highly generalizable to similar communities throughout the developing world.

CHAPTER 2

Coliform Sources and Mechanisms for Regrowth in Household Drinking Water in Limpopo, South Africa

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This chapter was accepted for publication in the Journal of Environmental Engineering.

Mellor, J. E., Smith, J. A., Samie, A., and Dillingham, R. A. "Coliform Sources and Mechanisms for Regrowth in Household Drinking Water in Limpopo, South Africa." Journal of Environmental Engineering. In Press.

2.1 Introduction

Worldwide more than 780 million people lack access to improved sources of drinking water, while a further 2.5 billion do not have improved sanitation. Improved water sources include those that are constructed to protect water from outside contamination such as protected springs or boreholes (WHO & UNICEF, 2012). Improved sanitation facilities are those that separate human excreta hygienically from human contact and are not shared. In resource-limited settings these are typically simple pit latrines.

This limited access leads to 1.6 million deaths each year of children under five years old (WHO, 2006). Repeated episodes of early childhood diarrhea (ECD) lead to serious problems such as stunting (Checkley *et al.* , 2008), long-term cognitive deficits (Niehaus *et al.* , 2002) and lower performance in school (Lorntz *et al.* , 2006). It is therefore imperative that community coliform sources and growth mechanisms be assessed in developing world communities to inform the implementation of interventions aimed at alleviating this burden.

Previous researchers have investigated pathogen sources within developing communities and have reported that household drinking water frequently becomes contaminated after collection but before consumption (Wright *et al.* , 2004). In addition, two major meta-analyses found that hygiene, sanitation and point-of-use water treatment devices were more effective in preventing diarrhea than community water source protection (Fewtrell *et al.* , 2005; Clasen *et al.* , 2007). Others have used complex systems approaches show that human behavior has a large impact on household water quality (Mellor *et al.* , 2012a).

Corroborating this evidence is the fact that several focused studies have found that point-of-use (e.g. household-level) water treatment technologies are effective at reducing water-borne coliform transmission (Schmidt & Cairncross, 2009; Kallman *et al.* , 2011). This is possibly because point-of-use systems treat water that might have been recontaminated during transport or storage. Point-of-use systems are typically simple, low-cost devices that treat water in the home for a typical family either through physical filtration, biological or chemical means (Schmidt & Cairncross, 2009). Ceramic water filters, solar disinfection and biosand water filters are some of the most common technologies. Alternatively households can chlorinate their stored drinking water which can likewise improve drinking water quality (Sobsey *et al.* , 2003).

All of these studies suggest that significant contamination occurs after collection and before consumption, but fail to pinpoint or quantify the different coliform sources.

One possible source of contamination are biofilm layers. Biofilm layers form when microorganisms attach themselves to a surface by secreting extracellular polymers. The new structure can create an environmental reservoir for pathogenic microorganisms making them resistant to antimicrobial treatment (Wingender & Flemming, 2011). Some researchers have tried to quantify biofilm layers (Jagals *et al.* , 2003) while others have suggested that water may frequently be recontaminated through hand-contact (Roberts *et al.* , 2001; Pickering *et al.* , 2010b). However, these studies were conducted under atypical conditions that do not represent average conditions in developing countries. The Robert's study had a small sample size of 10 participants and was conducted in a refugee camp with conditions that are atypical. Furthermore, the Pickering study was conducted with a mixed group of teachers, nurses and mothers in urban schools and health clinics making those results less applicable to a rural location inside an individual's household. Furthermore, it is possible that hand and water transfer device contamination could contribute to the formation of the biofilm layer on the insides of the water containers making concurrent measurement highly desirable.

In addition to the known presence of these coliform sources and methods to prevent the consumption of poor quality water, an unanswered question in the literature is the extent to which conditions suitable for coliform growth exist in household water storage containers in the developing world and how that might influence coliform growth or decay.

One possible source for these increased levels is declining residual chlorine concentrations due to long storage periods of community tap water that may lead to coliform regrowth if the water has suitable conditions. One study was conducted by LeChevallier *et al.* (1996) in the United States with a fully modern treatment and distribution system. It found that systems with low dead-end free chlorine levels had more occurrences of coliform bacteria. Another study by Roberts *et al.* (2001) found that chlorine levels declined with time in water storage containers, but the experiment was only 6 hours long, much shorter than typical storage periods in such settings. Although suggestive, neither of these studies accurately reproduces conditions typical in the developing world.

Coliform growth may also be affected by phosphorus, nitrates, dissolved oxygen (DO), chemical oxygen demand (COD), temperature, or organic carbon (Maier *et al.* , 2009). However, these associations have not been properly assessed in rural, developing world, communities.

Momba & Kaleni (2002) looked at regrowth on galvanized steel and polyethylene coupons suspended in water containers but not at regrowth in the bulk water. A second study by Vital *et al.* (2010) looked at biological regrowth using pre-cultivated bacteria strains in European water whose microbiota were likely very different from the microbiota found in a tropical environment. Nonetheless, these studies do indicate that bacterial regrowth might occur in the bulk water low-nutrient environments common in developing world storage containers and that it may depend on the amount of carbon and other conditions.

Therefore, biological regrowth in developing world water storage containers is a potentially important and under-studied phenomena in developing world settings. Vital *et al.* (2010) assess the extent of possible pathogen growth in controlled environments with three criteria. First, the pathogens must be present in the water. Second, there must be suitable conditions for growth. Lastly, the pathogens in question must compete with the autochthonous flora. A water source's suitability for regrowth can be assessed by measuring its assimilable organic carbon (AOC) concentration (Vital *et al.* , 2010).

AOC is the small (0.1-9%) fraction of total organic carbon (TOC) that can be readily assimilated by bacteria (Van der Kooij & Hijnen, 1985). It has a strong influence on bacteria regrowth and biofilm growth in previously-treated water systems in the developed world (van der Kooij *et al.* , 1992; Escobar *et al.* , 2001; van der Kooij, 2002). It can also be used as the limiting substrate concentration when modeling bacteria growth using the Monod equation (Vital, 2010):

$$\mu = \frac{\mu_{max} S}{K_S + S} \tag{2.1}$$

Where S is the substrate concentration, K_S is the half-saturation constant and μ_{max} is the maximum specific growth rate. Although AOC has been studied under controlled environments in developed countries by the aforementioned researchers, no studies have been carried out to assess AOC's presence or impact on biological regrowth in a tropical, developing world setting.

It is clear that there are significant knowledge gaps in scientists' understanding of coliform sources and growth mechanisms in a developing world community. It is also clear that a better understanding of these sources and growth mechanisms can inform the wider development community about ways to reduce coliform transmission in such settings thereby improving health of the world's most vulnerable. Therefore, the aim of this study is to investigate coliform sources and regrowth mechanisms in stored household water in a rural, South African community. This study contributes to the literature by investigating multiple different coliform sources in the same communities concurrently. It also investigates the biological and chemical changes that occur within a water storage container over the course of a week to better understand the parameters important for biological regrowth, including levels of AOC.

2.2 Methods

2.2.1 Field Site Setting and Household Selection

This study was carried out in the adjacent, rural communities of Tshapasha and Tshibvumo in Limpopo, South Africa. Limpopo Province is South Africa's second poorest and most rural province (90% of its people live in rural areas) (Lehohla, 2006, 2011). Diarrhea is the second leading cause of death amongst children under four years of age (Bradshaw *et al.* , 2008). In addition, diarrhea rates are 1.7 times higher than the national average and have increased 170% between 2003 and 2008 in Vhembe District, Limpopo (Sello, 2010).

A pre-study assessment found that community members get water from three main sources: surface water (SW) from a stream bisecting the two communities, municipal taps (MT) operated by the local municipality and a community piped (CP) water system. MT water is treated (including chlorination) by the Mutale municipality and piped to communal standpipes located throughout the communities. The Mutale municipality water supply was recently rated as having "Excellent Drinking Water Quality Compliance" in the 2012 Blue Drop study which assessed drinking water quality throughout South Africa (DWA, 2012). However, the MT system is unreliable - households reported for this study that water does not flow 31.6% of the time (n = 50).

CP was a poorly performing development project that was improved through a collaborative effort between University of Virginia and University of Venda students and faculty with substantial community support (Harshfield *et al.* , 2009; Heil *et al.* , 2010). It consists of a series of pipes that bring stream water down from hills behind the communities to a storage tank where it may be chlorinated and sent to standpipes in selected households. However, the pre-study assessment found that the water is rarely chlorinated. This system is likewise unreliable with households reporting for this study that they cannot get water 45.4% of the time (n = 50).

Forty-nine (or approximately 48%) of the total number of households in Tshapasha and Tshibvumo with children under 5 years old were selected to participate in the study. Although logistical and practical constraints prevented random selection, they were chosen to represent as broad a geographic and socio-economic cross section of the communities as possible and include nearly every household that was willing and able to participate in the study. Among them a subset of 14 households (9 MT and 5 CP households) was selected to participate in the monthly testing. This smaller subset was chosen for their co-participation in The Interactions of Malnutrition & Enteric Infections: Consequences for Child Health and Development (Mal-ED) project (Lang,

2011) and to represent the MT and CP community water sources. Finally, a second subset of 12 households was chosen from the larger pool that represented the two main types of water storage containers - “narrow” and “wide” neck and the three water sources. These containers are shown in Figure 2.1. These 12 households were asked to relinquish their water storage containers for a 7-day incubation experiment. A Venn diagram describing all three cohorts in given in Figure 2.2.

Figure 2.1: *“Wide” and “Narrow” neck household water storage containers were the two container styles most commonly used in the communities.*

All households were surveyed about their water and sanitation practices and knowledge in the regional language of Venda. “Good”, “OK” and “Poor” water container washing techniques were assessed by asking participants how they washed their storage containers. Those who reported scrubbing with soap had a “Good” technique. Those who reported either using soap or a scrubbing had an “OK” technique and those who just rinsed it had a “Poor” technique. In addition, households were queried about their water treatment practices and latrine prevalence.

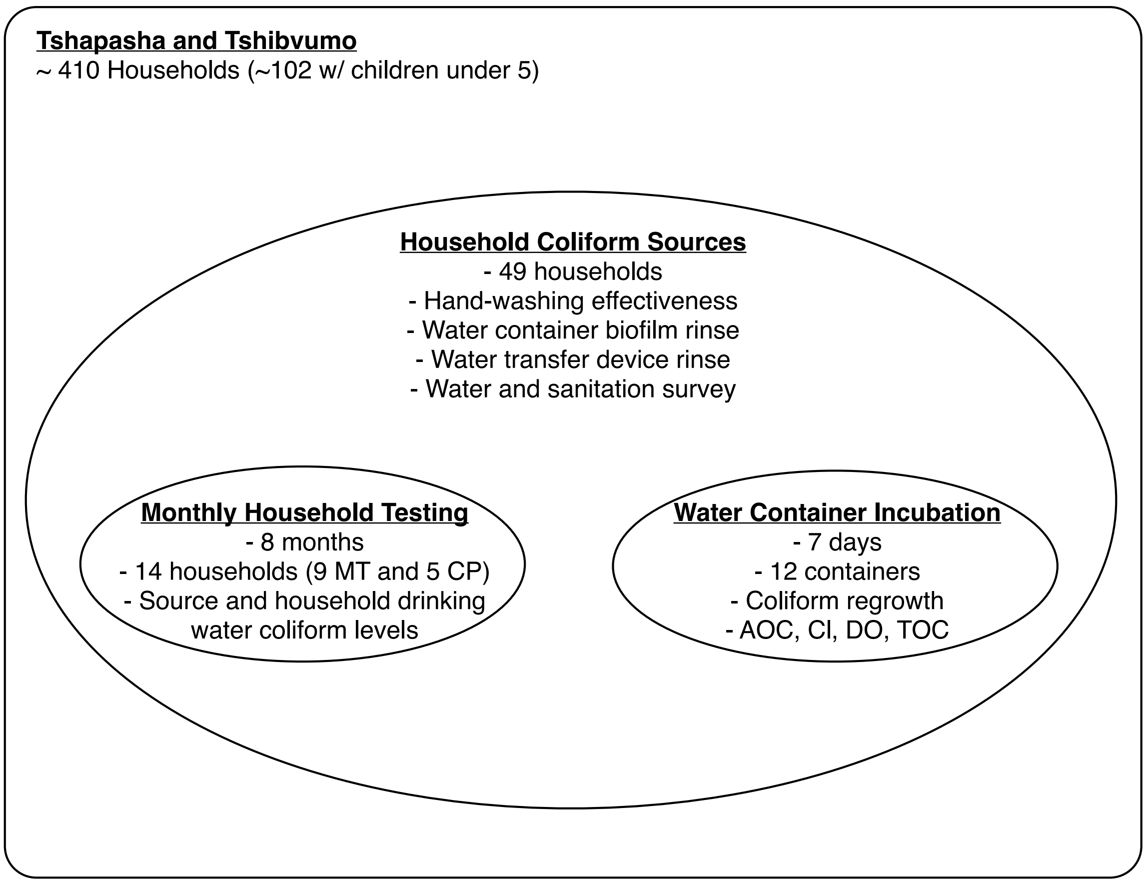

Figure 2.2: *Venn diagram describing the study participants.*

2.2.2 Field Sampling Methods

Monthly water sampling in the household as well as measurements of contamination of hands, water containers and water transfer devices were all measured in the communities.

Monthly water sampling was carried out through household visits. Each household was asked to produce approximately 100 mL of "drinking water" which was poured into a sterilized Whirl-Pak (Nasco) bag containing 10 mg sodium thiosulfate. No accounting was done for potential cross-contamination from household water transfer devices because the stated goal was to measure the quality of water as actually consumed. The term "drinking water" was used because many households also keep presumably inferior quality water for other domestic uses such as washing.

Hand-contamination was measured before and after washing using the protocol described by Pickering *et al.* (2010a). In brief, the participants were asked to fully immerse one randomly selected hand into a sterilized 2 L Whirl-Pak bag filled with 500 mL of bacteria-free water and agitate it for 30 seconds. After being asked to wash their hands as they normally would, participants were asked to immerse and agitate their other hand in a second bag for 30 seconds. There are no strong cultural norms that would make one hand more contaminated than the other in the Limpopo region.

Biofilm buildup was measured using a sterilized swirl protocol (Roberts *et al.* , 2001). Water storage containers were emptied out and 500 mL of sterilized water was introduced. The containers were then capped when possible and vigorously shaken by hand for 15 seconds. The effluent was then collected and measured for coliform bacteria.

Water transfer devices (typically a cup or ladle) were analyzed by fully immersing them in a 2 L Whirl-Pak bag filled with 500 mL of sterilized water and agitating the water for 10 seconds. The transfer device was then aseptically removed and the water measured for coliform bacteria.

All samples were kept on ice in a portable cooler during transport back to the laboratory. Samples were tested within 24 h.

2.2.3 Water Container Incubation

As mentioned above, 12 water storage containers were procured from study participants. The 12 containers were divided into three groups of four based on the source water used by the participants (MT, CP and SW). These containers were then filled with 20 liters of water from the participants' primary water source and incubated indoors for 7 d. During this time, the containers were not disturbed except for aseptic sampling. The water maintained a nearly constant temperature of 19^{o}C throughout the experiment.

2.2.4 Analytical Methods

Biological contamination was quantified using m-ColiBlue24 Broth (Millipore, Billerica, MA) as a growth medium to detect total coliform bacteria using membrane filtration. Each sample was first diluted by a 1:10 or 1:20 ratio using sterilized, unbuffered, deionized water. It was then passed through a 0.45 μm Fisherbrand (Pittsburgh, PA) Water-Testing Membrane Filter, incubated for 24 h at 35^{o}C and the colonies were counted visually. Periodic blank samples all showed zero colonies.

Coliform concentrations for the hand contamination experiment were normalized and results are reported in terms of CFU/hand. Results for the water storage container biofilm rinse experiment were normalized by container surface area and results are reported in terms of CFU/cm^2. Finally, results for the water transfer device were also normalized and reported as CFU/device.

Turbidity was measured using a Hach Turbidimeter with units reported in NTU.

Assimilable Organic Carbon (AOC) was measured with a bioassay and the standard flow-cytometric method (Hammes & Egli, 2005). A natural water sample from the river bisecting the communities was collected and filtered using a pre-rinsed 0.22 μm syringe filter (BD, Franklin Lakes, NJ) to remove bacteria and interfering particles. The filter was pre-rinsed with sterilized DI water. Filtered water was then reinoculated with 10 $\mu L/mL$ of river water and incubated in a rotating incubator at 30^{o}C for 7 d to produce the inoculum.

Experimental samples were collected of which 15 mL were filtered using pre-rinsed syringe filters into AOC-free glassware. The sample was then inoculated with 30 μL of inoculum after which it was capped and incubated in a rotating incubator at 30^{o}C for 48 h.

Positive controls were prepared similarly using various concentrations of sodium acetate (Fisherbrand, Pittsburgh, PA) in commercially available bottled water. Negative controls contained only bottled water.

All glassware used for collection, processing and incubation was made AOC free. AOC was removed from glassware by soaking it for 12 h in 0.1 N HCl, rinsing it with deionized water and heating it to 500 ^{o}C for 5 h in a furnace. Teflon-coated caps were soaked in a 10% sodium persulfate solution for 1 h, rinsed with deionized water and air-dried.

After incubation, cells were lysed using a Beckman Coulter DNA Prep Lysis Buffer and enumerated using a Beckman Coulter Cytomics FC 500 Flow Cytometer and CXP Software. That unit has a 488 nm, 100 mW argon-ion laser. Green and red florescence was collected on the FL1 and FL3 channels respectively. Instrumental gains were 551 for FL1 and 250 for FL3 and acquisition time was 300 seconds for each sample.

Total organic carbon (TOC) and free chlorine were measured photometrically using a Hach DR/890 Portable Colorimeter. Hach Method 10129 was used for TOC. Hach method 10069 which is equivalent to Standard Method 4500-C1-G for drinking water was used to measure free chlorine. Dissolved oxygen (DO) was measured using a Vernier Dissolved Oxygen Probe (DO-BTA) which was interfaced to a computer using a LabQuest Mini. The DO data was collected using Logger Pro 3 software.

2.2.5 Statistical Analyses

Statistical analyses were carried out using R Statistical Computing Package and Microsoft Excel. Student's t-tests, paired t-tests and ANOVA analyses were conducted where appropriate. All statistical tests were done at 95% confidence levels. All boxes in the boxplots represent the median, upper, and lower quartiles. The whiskers represent the lowest and highest data still within a 1.5 x inter-quartile range from the median while the outlying circles represent data outside that 1.5 x inter-quartile range.

2.3 Results

2.3.1 Monthly Household Testing

Water in the communities is obtained from three main sources: municipal taps operated and chlorinated by the local municipality (MT), a piped water system operated by community members (CP) and surface water (SW) from a nearby river. 57% of participants reported getting their water from the CP system, 25% from MT and 17% from SW. When a household's primary water source is not working, 63% of the total households use SW, 25% CP and 12% MT. Water source availability is highly variable forcing residents to frequently store their drinking water for an average of 3.0 ± 0.6 d (n = 47). Although most houses (93.8%) have latrines, few households (18.8%) reported treating their water.

Monthly water testing carried out from December 2011 through July 2012 indicates that a significant increase in coliform levels occur between sources and households. Overall, water quality deteriorated between source and household from 197 to 1046 CFU/100 mL (n = 266, $p < 0.001$) on average for all households surveyed. The MT water system showed an increase from 88 to 1098 CFU/100 mL (n = 132, $p < 0.001$) on average while the CP system also showed a significant increase, 334 to 948 CFU/100 mL (n = 134, $p < 0.001$). Data for the MT and CP systems are shown in Figures 2.3 (a) and (b) respectively. For comparison, water collected from untreated local surface water sources averaged 938 ± 223 CFU/100 mL (n = 52).

It is possible that seasonal variations were observed in the data as can be seen in Figure 2.4. Kruskal-Wallis Rank Sum Tests concluded that the monthly variations were significant for the MT system ($\chi^2 = 24.95$, degrees of freedom = 7, p-value =

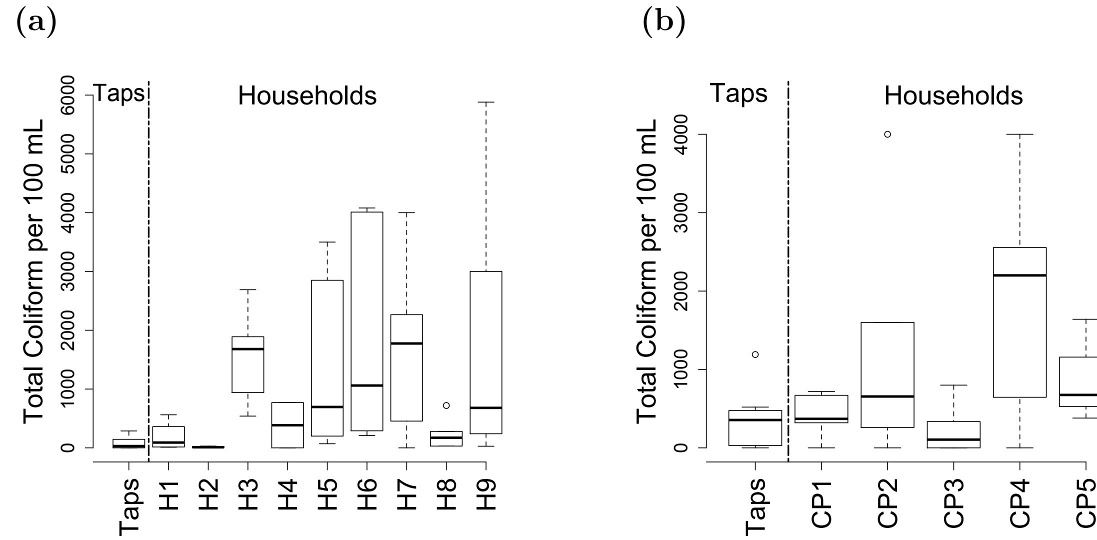

Figure 2.3: *Boxplots of source and household water quality for (a) MT (municipal tap) and (b) CP (community piped) water systems. Taps and households are aggregated to the left and right respectively of the dashed line in each plot. Eight consecutive months of data is given for the participating households. In MT, the data show a significant increase in coliform levels between the municipal taps (MTs) and the households (88 to 1098 CFU/100 mL (n = 132, p < 0.001)). Likewise boxplots of CP show a significant increase in coliform levels between the CP taps and the households (334 to 948 CFU/100 mL (n = 134, p < 0.001)).*

0.001). The CP variations were likewise significant ($\chi^2 = 16.67$, degrees of freedom = 7, p-value = 0.020). However, these variations could be also produced by sampling error.

2.3.2 Household Coliform Sources

Hands proved to be a significant source of coliforms both before and after hand-washing with high concentrations of coliform bacteria being measured in the rinse water. Average before and after levels were 5097 and 3903 CFU/hand respectively (p = 0.320, n = 48). However, dirt was effectively removed as indicated by the significant

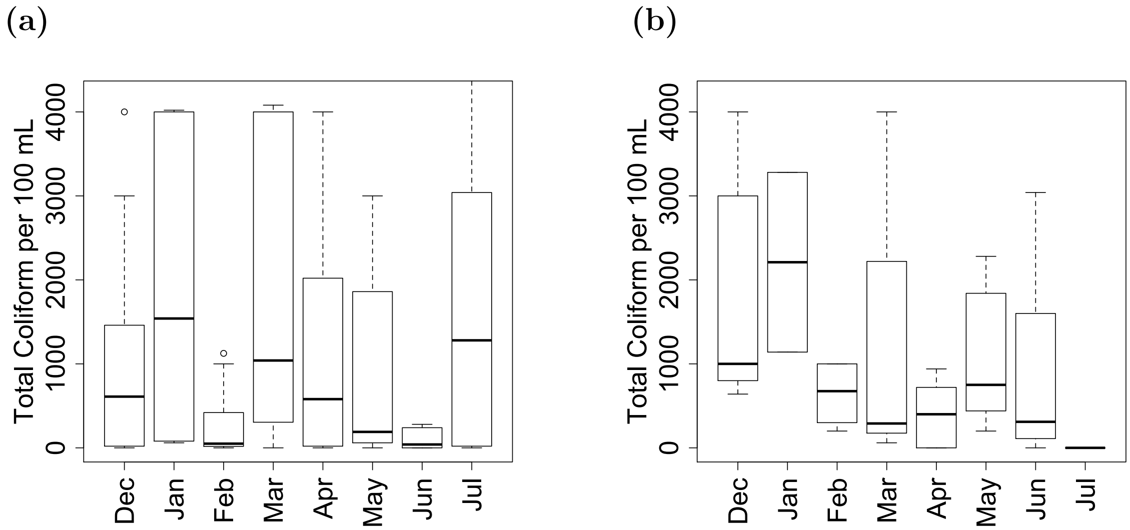

Figure 2.4: *Boxplots of eight consecutive months of household water quality in the communities for the (a) MT (municipal tap) and (b) CP (community piped) water systems. The data indicates significant inter-monthly variations (p = 0.001 and p = 0.020 for MT and CP respectively), which could possibly indicate seasonal variations.*

decrease in turbidity of the rinse water - 2.82 vs 0.81 NTU (p = 0.014 , n = 48). These data are shown in Figure 2.5.

Measurements of the biofilm layer on the inside of household water storage containers indicated that a significant and highly variable amount of coliform bacteria are associated with the sidewalls: 1.85 ± 1.59 CFU/cm^2. This association shows no significant variance with container type: 1.71 and 2.35 CFU/cm^2 respectively for "narrow" neck versus "wide" neck type containers (n = 40, p = 0.683). There was no correlation between reported washing techniques and biofilm layers. Those with "Good", "OK", and "Poor" techniques had total coliform levels of 3.02, 0.63 and 0.95 CFU/cm^2 respectively $F(2, 36) = 0.966$, p = 0.390. Primary drinking water source was also not a significant factor: 1.22 vs 2.49 CFU/cm^2 for CP vs MT (t = 2.022 n = 40 p = 0.528). Neither reported "time since last washing" nor "collection frequency" showed

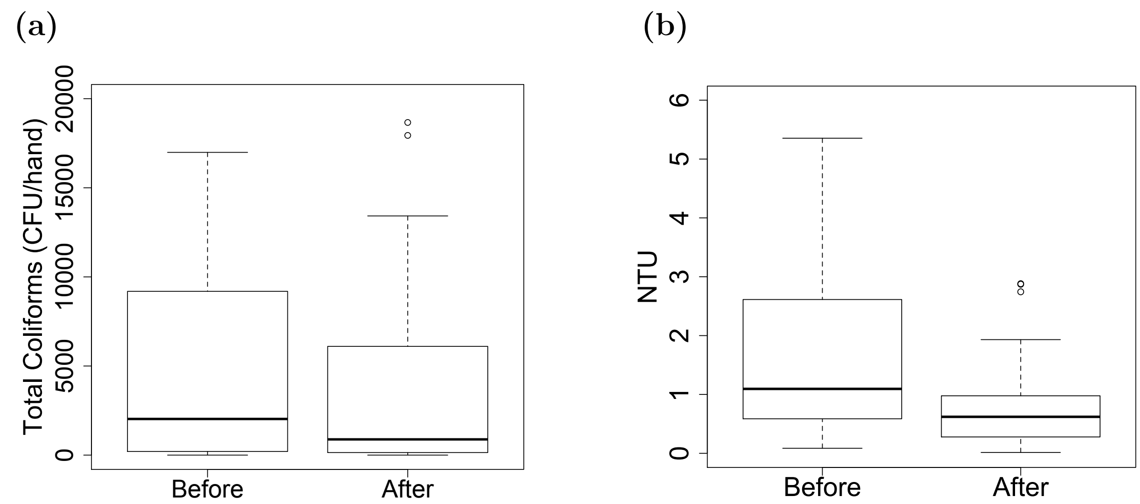

Figure 2.5: *(a) Total coliforms and (b) turbidity before and after hand-washing. Hands contained a significant amount of total coliforms before (5097 CFU/hand) and after (3903 CFU/hand) hand-washing (p = 0.320, n = 48). However, hand-washing was effective at reducing turbidity, a proxy for dirt, on the hands of the participants with before and after values of 2.82 and 0.81 NTU respectively (p = 0.014 , n = 48).*

a significant correlation to biofilm levels ($R^2 = 0.004$, p = 0.666 and $R^2 = 0.009$, p = 0.556 respectively). Water transfer devices were also a source of coliforms in many households as indicated by the contamination of the water they were immersed in. The average level of total coliform bacteria found was 2513 ± 1689 CFU/device.

2.3.3 Water Container Incubation

The incubation experiment of water from different sources stored in containers found a significant increase in total coliform bacteria for the SW and CP containers over the course of 7 d while MT showed little increase. Figure 2.6 (a) indicates that chlorine levels in MT remained significant throughout the week, while those in CP and SW were negligible. As can be seen in Figure 2.6 (b), coliform levels in CP water

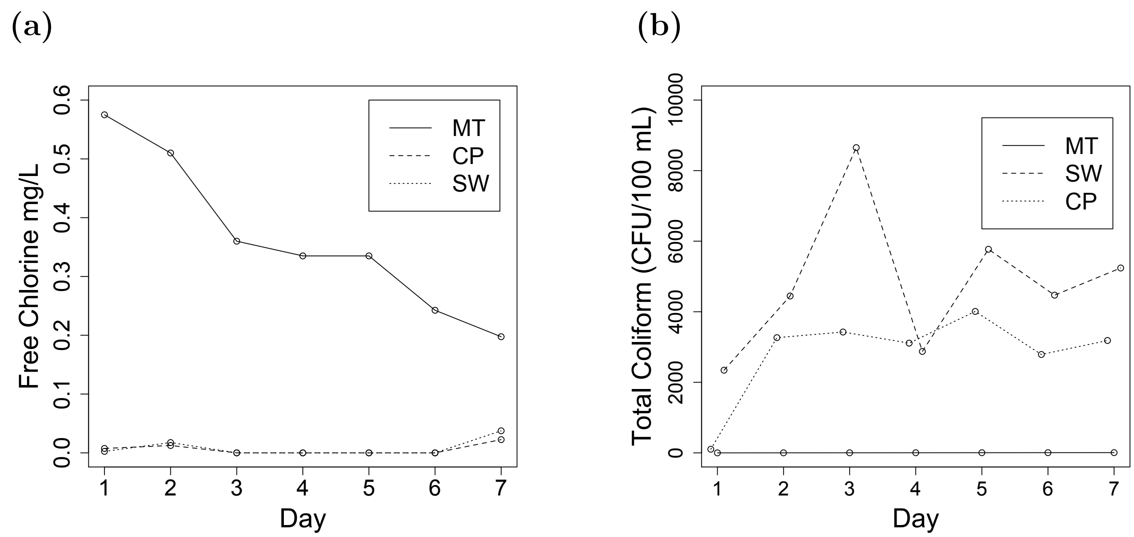

Figure 2.6: *(a) Free chlorine levels for the water containers. MT (municipal tap) water maintained significant chlorine levels throughout the week while CP (community piped) and SW (surface water) levels remained negligible. (b) Total coliform levels throughout the seven day incubation experiment. Results indicate significant regrowth in all cases except the MT system.*

containers increased from 103 ± 19 to 3265 ± 2495 CFU/100 mL after the first day. The SW system containers increased from 2343 ± 3746 to 4446 ± 1958 CFU/100 mL after the first day and to 8653 ± 2363 CFU/100 mL after the second day. This corresponds to growth rates of 0.14 h^{-1} for CP and 0.03 h^{-1} for SW. Coliform levels did not rise significantly in either system after the second and third days respectively during which time they may be entering a stationary phase. Water containers used for the MT system saw little coliform growth for the entire seven days.

The type of storage container made a significant difference with weekly average coliform levels of 1,771 vs 5,072 CFU/100mL for "narrow" neck versus "wide" neck containers (paired t-test, $p = 0.001$) as is shown in Figure 2.7. TOC levels decreased throughout the week according to a first-order exponential decay (log-linear fit $R^2 =$

0.805, $p = 0.039$ and $R^2 = 0.750$, $p = 0.026$ for "narrow" and "wide" neck respectively) as seen in Figure 2.8 (a). "Narrow" neck containers might possibly have had somewhat lower daily levels than "wide" ones but the difference was not significant (2.0 vs 2.3 mg/l for "narrow" neck vs "wide" neck paired t-test, $p = 0.156$). DO concentrations decreased according to a first-order exponential decay throughout the week (log-linear fit $R^2 = 0.569$, $p = 0.050$ and $R^2 = 0.623$, $p = 0.035$ for "narrow" and "wide" neck respectively) as is shown in Figure 2.8 (b). The weekly average DO levels in the "narrow" neck containers was significantly more than the "wide" neck type containers (8.2 vs 7.6 mg/l $p = 0.001$, paired t-test).

Finally, AOC measurements performed on day 1 indicated levels of 7 to 840 μg/L. These results were poorly correlated with container type. "Narrow" neck containers had less AOC than "wide" neck ones (67.3 vs 257.7 μg/L for "narrow" and "wide" neck respectively, $p = 0.409$). There was a significant correlation between the ratios of first to second day coliform levels and AOC concentration ($R^2 = 0.866$, $p = 0.002$) as is highlighted in Figure 2.9 (a). However, the exclusion of the largest data point reduces the significance of the correlation ($R^2 = 0.550$, $p = 0.091$). The data was fit to a Monod growth resulting in a μ_{max} of 0.072 ± 0.003 h^{-1} and K_S of 10.209 ± 2.504. The best fit is shown in Figure 2.9 (b).

2.4 Discussion

The water sources in these communities represent water sources typically used in many developing world communities (Thompson, 2001). However, the surveys indicate that water collection is complicated by the fact that residents commonly store their water for extended periods. Furthermore, they sometimes switch to alternate,

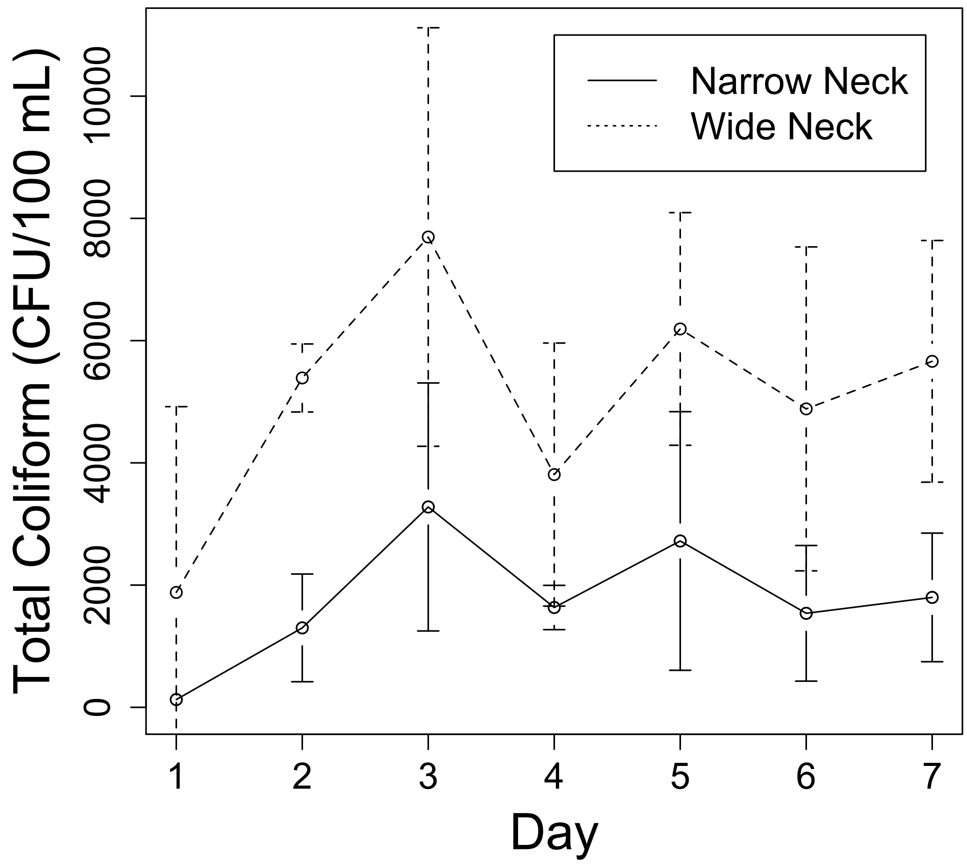

Figure 2.7: *"Narrow" neck containers showed a significantly lower level of total coliform re-growth during the incubation period. Data excludes MT (municipal tap) containers.*

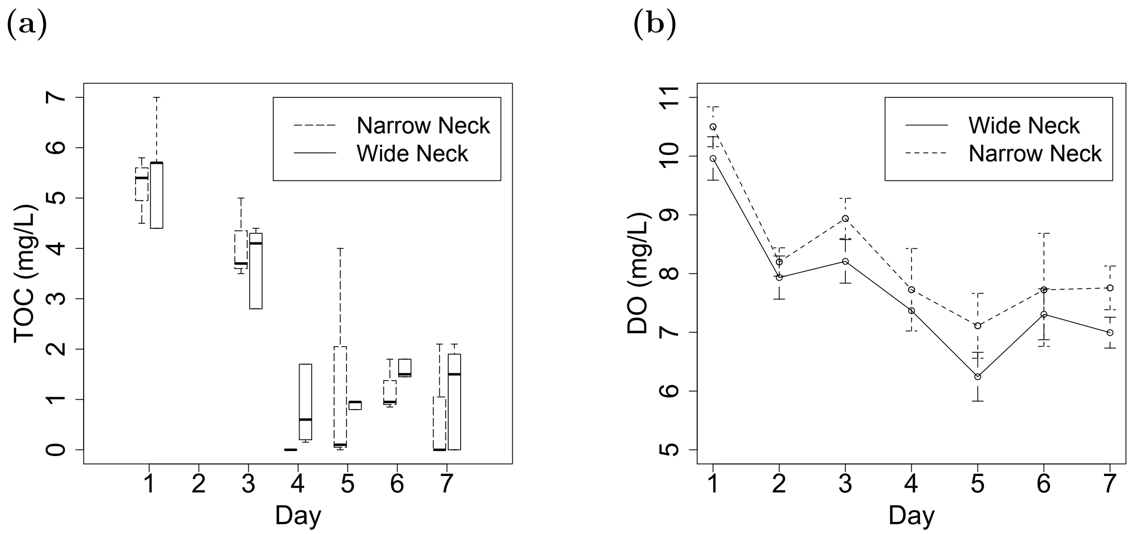

Figure 2.8: *(a) "Wide" and "narrow" neck containers both exhibited a similar decline in TOC concentrations throughout the week, with "wide" mouth containers having possibly somewhat higher levels - 2.0 vs 2.3 for "narrow" neck vs "wide" neck although the difference was not significant (paired t-test p = 0.156). (b) DO decreased uniformly throughout the week, but "wide" neck containers showed lower daily levels (8.2 vs 7.6 p = 0.001, paired t-test). Data excludes MT (municipal tap) data.*

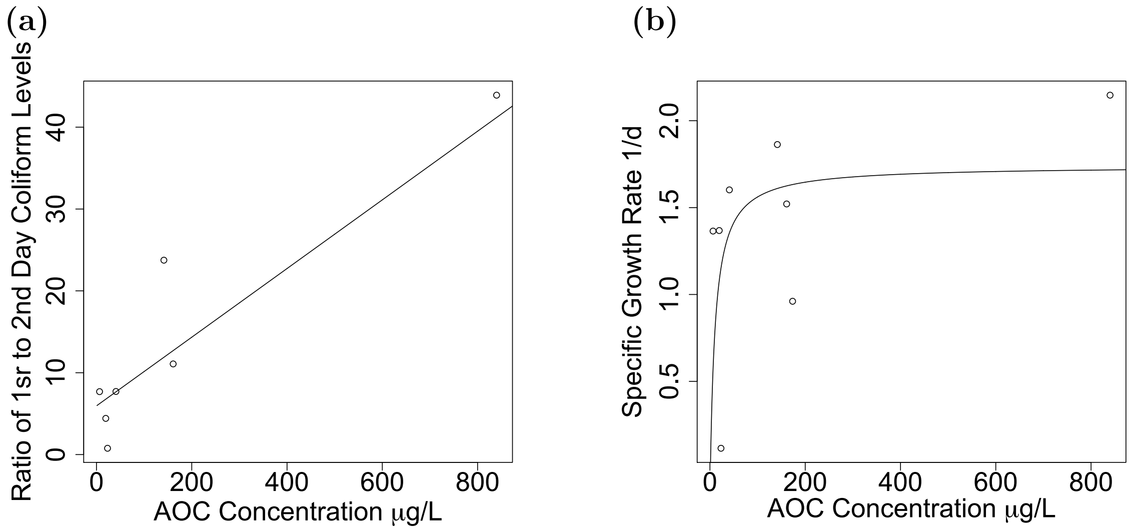

Figure 2.9: *(a) AOC concentrations (μg/L) vs ratio of first to second day total coliform levels. Shows a strong linear trend with R^2 = 0.866 (p = 0.002). (b) Monod plot of AOC concentration vs specific growth rate. Data indicates μ_{max} of 0.072 h^{-1} and K_S of 10.209. Data excludes MT (municipal tap) data.*

less desirable sources when their primary sources are inoperable for some time. The fact that few residents boil their water coupled with the data obtained above, indicates that residents frequently consume contaminated water.

As was found by others (Wright *et al.* , 2004), the increase in total coliform levels recorded between source water and household (irrespective of source water type) indicate that a substantial coliform loading occurs along the water chain between source and consumption. This increase was seen consistently each month. In addition, substantial heterogeneity was apparent even within single households indicating that households may have good and bad months. Although, since samples were only taken monthly, it is unclear if the measurements represent true seasonal variation or sampling error. These facts indicated that there may be opportunities for improvements and dispersion of best-practices within communities and that human behaviors may have a significant effect on drinking water quality (Mellor *et al.* , 2012a).

The biofilm measurements indicated that household storage containers might be a significant and highly variable source of recontamination and are consistent with previous studies by Jagals *et al.* (2003) conducted in South Africa. Jagals found median total coliform levels of 158 CFU/100 mL which is similar to the unnormalized 120 CFU/100 mL found in this study which used a similar methodology. Even when cleaned frequently, results indicated that the sidewalls contained coliform bacteria. "Narrow" neck containers, which are more difficult to clean, may have been somewhat cleaner on average in this study since they prevent hand contamination and do not require a transfer device, but the differences are not significant. A similar result was found by others (Jensen *et al.* , 2002; Maraj *et al.* , 2009). Trevett *et al.* (2005) found a lower percentage, 27% (n = 8) vs 63.6% (n = 44), of contaminated water transfer devices. This might have been because they were testing for thermotolerant coliforms and had a smaller sample size. The high heterogeneity seen in this study is consistent with previous research and conforms to field observations about the acute differences in observed water container cleanliness.

The results from the hand experiment are likely a result of the inadequate hand-hygiene practices of the survey participants. Traditionally, hand-washing is done in a communal, open water basin with highly turbid water and without soap. Unprompted to do so, only 12.5% (n = 48) of the study participants used soap when washing their hands for this study and 87.5% (n = 48) washed their hands in an open basin or bucket. Although this method is adequate for rinsing off dirt, it is ineffective at removing bacteria. As was found in previous studies, improper hand-hygiene might therefore be a significant source of coliforms in the community (Pickering *et al.* , 2010b) which might lead to diarrhea (Aiello *et al.* , 2008). The percentage of positive results are higher than has been found previously by Trevett *et al.* (2005) who found a lower percentage 44% (n = 14) of contaminated hands than was found in this study, 96% (n = 48). Improved hand-washing regimes might therefore represent a significant area for coliform reduction in the communities.

Summarizing, water transfer devices and dirty hands likely both contribute to the excess of coliform bacteria found on the sidewalls of “wide” necked containers and hence in the poor household water quality. Therefore, based on the results of this study, “narrow” neck containers are preferable.

The incubation experiment investigated the growth of coliforms in a household storage container irrespective of human interference. Results indicate that coliform levels increase exponentially during household storage and this growth might be attributable to AOC concentrations. After this rapid exponential growth, the coliform bacteria appear to enter a stationary phase around day 3 during which time the coliform concentrations do not rapidly rise. This may correspond to a period in which an essential nutrient is exhaused with the dying cells providing that nutrient while the cells continue to consume carbon (Maier *et al.* , 2009). TOC and DO levels declined as expected given the marked increase in bacteria levels coupled with a leveling off after day 3. TOC may have been somewhat higher (although the results were not statistically significant) and DO was lower in “wide” neck containers which is consistent with the increased levels of biological growth seen in the “wide” neck containers. The potential TOC difference could be due to carbon introduced by water transfer devices or dirty hands. It is not clear from the data what growth stage the coliform bacteria is in. However the large drop in TOC could be a result of a steady state situation in which the bacteria are dividing and dying while consuming considerable amount of carbon. One caveat to these findings are the correlations between “wide” and "narrow" neck total coliform and DO levels seen in Figures 2.7 and 2.8 (b). It is possible that these correlations could represent a systematic bias. This is particularly seen in the day 2 to 3 increase in DO levels in Figure 2.8 (b). However, this variation is within the 95% confidence intervals and could simply represent random errors.

The long storage periods in this and similar communities throughout the developing world coupled with long collection distances (Mellor *et al.* , 2012c) typical in such settings may mean that coliform regrowth might be a significant and under-studied factor in household water contamination. The regrowth seen is consistent with a previous study, in which biological regrowth did occur within 48 h (Momba & Kaleni, 2002). Another study by Roberts *et al.* (2001) showed moderate biological growth for the first six hours after collection. Neither study measured bacteria levels after these periods. Finally, the lack of any growth in the MT water and the consistently adequate chlorine levels indicate that chlorination is a sufficient method for preventing biological regrowth in such settings. However, the monthly household collections indicate that even when residents get water from previously chlorinated supplies (MT) it can get contaminated in the home likely due to contaminated hands and water transfer devices.

The maximum specific growth rate found (0.072 ± 0.003 h^{-1}) for total coliforms is consistent with the rate previously measured by Vital (2010) who found 0.04 h^{-1} for *E. coli* in natural water at 20^{o}C. The difference could be due to the different bacteria types. In addition, this study looked at indigenous coliforms that must compete with other indigenous bacteria while the Vital study looked only at isolated pure culture growth.

In addition, the AOC concentrations measured on Day 1 are strongly correlated with the growth potential as is seen in the strong correlation between AOC concentrations and the second to first day coliform increase. Vital *et al.* (2008) similarly found a positive correlation between AOC and final concentration after a 3 day incubation. Therefore, high AOC concentration might be an important predictor of coliform regrowth potential in the first couple of days. However, the lack of correlation between Day 1 AOC concentrations and the weekly average concentration may suggest that AOC is consumed after the first couple of days when the bacteria concentrations leveled off.

AOC concentrations above 100 μg/mL are significant because they can lead to biological growth of harmful pathogens such as cholera (Vital *et al.* , 2007) or *E. coli* (Vital *et al.* , 2008). 50% (n = 8) of the samples had AOC concentrations higher than this value. In addition, Vital *et al.* (2010) found that the growth potential for a variety of bacterial strains can be 10^6 cells/mL or higher for AOC concentrations in the ranges found in this study. This research is also important because it suggests that higher residual chlorine levels or point-of-use water treatment technologies may be necessary in developing world settings when AOC levels might be elevated (LeChevallier *et al.* , 1996). Since point-of-use drinking water devices treat water in the household ideally just before consumption, they minimize the possibility that water might become recontaminated.

Finally, this study has some limitations that warrant some discussion. First of all, it is unclear how the prevalence and regrowth of the total coliform indicator bacteria corresponds to the prevalence and regrowth of the different diarrhea pathogens. Despite this fact, total coliforms are frequently used by researchers as an indicator of bacterial regrowth (LeChevallier, 1990) as well as inadequate water treatment (EPA,

1989) which were studied in this paper. Furthermore, the presence of total coliform bacteria can indicate that other harmful bacteria may be present (EPA, 1989). Future research should investigate the possibility of pathogen regrowth possibility including viruses, protozoa, parasites and other known diarrhea-causing pathogens.

2.5 Conclusion

Results from this study indicate that water is frequently contaminated after collection, but before consumption. Both hands and transfer tools are significant sources of total coliform bacteria and may contribute to the formation of biofilm layers. The biofilm layers and high AOC levels found are likely the source of the coliform regrowth measured. Evidently long storage periods due to frequently inoperable water sources coupled with biochemical conditions favorable for regrowth lead to significant re-contamination of water sources. The fact that no regrowth was seen in the chlorinated municipal tap water indicates that the residual chlorine provides important protection against re-contamination. “Narrow” neck containers are generally preferable because they reduce the likelihood that container insides might be contaminated by hands or water transfer devices. They also had less biological regrowth in this study. The high heterogeneity in coliform levels seen in this study indicate that best and worst practices are prevalent within communities. The spreading of these best practices might be a means of reducing coliform levels in poorly performing households. In conclusion, interventions that focus on increased reliability of water sources, chlorination and point-of-use technologies as well as improved hand-washing techniques and spreading of best practices can all have a significantly positive impact on reducing coliform bacteria within a community.

CHAPTER 3

ABM Development and Analysis

This chapter was published in Environmental Science & Technology in 2012:

Mellor, J. E., Smith, J. A., Learmonth, G. P., Netshandama, V. O., and Dillingham, R. A. (2012). "Modeling the complexities of water, hygiene, and health in Limpopo Province, South Africa." Environmental Science Technology, 46(24), 13512 - 13520.

The Supporting Information for this manuscript is reproduced in Appendix A. Included in that appendix are details regarding data collection, the model's architecture as well as a number of other behavior space and sensitivity analyses.

3.1 Introduction

Poor access to adequate water and sanitation infrastructure is an important contributor in over 2 million deaths and 82 million disability-adjust life years (DALYs) that occur throughout the world each year (Prüss *et al.* , 2002). This disease burden has a number of negative effects including child growth stunting which can result from episodes of early-childhood diarrhea (ECD) (Checkley *et al.* , 2008).

Previous researchers have attempted to pinpoint the causes and prevention strategies for such preventable diseases using meta-analyses of conventional intervention-control trials (Esrey *et al.* , 1985; Fewtrell *et al.* , 2005; Clasen *et al.* , 2007). However, these studies looked at the effectiveness of each intervention in isolation, a technique that fails to acknowledge the complexities of water and sanitation in such settings. The large heterogeneity seen in these meta-analyses is a further indicator of the inability of single-intervention studies to elucidate the problem. It could also partially be due to difficulties in using self-reported ECD as an indicator of poor water quality (Schmidt *et al.* , 2011) or heterogeneity in intervention effectiveness.

The myriad of pathogen sources within a typical developing-world community and the potential for biological regrowth (Mellor *et al.* , 2012b) leads one to consider the fact that poor quality water is related to multiple technological, environmental and behavioral factors (Ezzati *et al.* , 2005). It is this sort of thinking that has led some to suggest that a systems approach to enteric pathogen transmission would contextualize transmission and inform prevention and control efforts (Eisenberg *et al.* , 2012). Along these lines, one study found that single-pathway intervention strategies are not effective at preventing diarrhea and that successful interventions must interrupt all significant pathways (Eisenberg *et al.* , 2007). However, this study was based on a hypothetical disease transmission scenario using adjusted parameters. A second study used the quantitative microbial risk assessment technique although their study was limited to household water treatment devices (Enger *et al.* , 2012b).

One promising approach is to use an agent-based model (ABM). ABMs are object-oriented, spatial models that are currently used in diverse fields to study complex systems. Complex systems do not have any central, coordinating mechanism so that system-level behaviors cannot be predicted based on knowledge of the individual components. These systems can exhibit *emergent* behavior which can lead to valuable information that would have been difficult to predict *a priori*.

ABMs typically consist of agents who operate under certain behavior rules in a constructed environment (An, 2009). The technique is increasingly being used by public health experts who have studied the H1N1 influenza (Shi *et al.* , 2010) and insecticide-treated mosquito nets for the prevention of malaria (Gu & Novak, 2009). ABMs allow researchers to investigate the essential components of a system *in silico* negating the need for costly intervention-control trials.

Therefore, the purpose of this research is to develop a robust, quantitative understanding of the complex water chain whose contamination leads to ECD. This model focuses on the transmission of coliform bacteria, but could be generalized to other pathogens. This will be done using an ABM informed by four years of data from adjacent communities in Limpopo, South Africa that will be used to learn more about the causes and prevention strategies of poor household water quality and ECD in such settings. The results of this study can be used by future researchers to design the most effective interventions in similar communities worldwide.

3.2 Methods

3.2.1 Community Setting

This ABM is based on four years of data from the adjacent communities of Tshapasha and Tshibvumo in Limpopo, South Africa. Limpopo is the second poorest and most rural province in South Africa. Diarrhea is the second leading cause of death amongst children under four years of age (Bradshaw *et al.* , 2000). In addition, diarrhea rates are 1.7 times higher than the national average and have increased 170% between 2003 and 2008 in Vhembe District (Sello, 2010).

Residents of Tshapasha and Tshibvumo get water from one of three different systems (Mellor *et al.* , 2012b). The first source, referred to herein as "surface water" (SW), is a stream bisecting the communities. Community piped (CP) is a community water system that was improved through a joint effort between the University of Virginia and the University of Venda (Harshfield *et al.* , 2009). In this system a series of pipes brings river water from above the community. This water is then sent through a slow-sand filter system, a chlorination tank and into a piped water system for distribution to households. However, the slow sand filter system is currently inoperable and community members report that the chlorination tank is infrequently chlorinated. Municipal tap (MT) is a municipal water system operated by Mutale municipality which is considered to have good water quality (DWA, 2012), but is highly unreliable.

3.2.2 Modeling Environment

The ABM was written in Netlogo, a graphical multi-agent programming language useful for modeling complex systems (Tisue & Wilensky, 2004; Railsback & Grimm, 2011). The model was adapted from an earlier version (Demarest, 2011). It includes two types of agents: households and children. The 410 households are laid out across the two communities using measured GPS coordinates. Children are born to individual households in the community at a randomized average rate of 21.9 per year, consistent with a community census performed in 2009.

Each model "tick" corresponds to a "day" of life in the communities and simulation runs are typically 30 years in length. This period allows the simulation to reach equilibrium while providing enough statistical significance for the results to be interpretable. This period corresponds to approximately 657 children being born and 4.49×10^6 household-days.

Variables "owned" by each one of the two agent types are summarized in Table 3.1. Variables such as primary water source and sex are constant for each respective household and child, while variables such as child ECD status can change daily. Global variables used by all agents are shown in Table 3.2. Further details about how variable values were measured are given in subsequent sections, Chapter 2 and Appendix A.1.1.

3.2.3 Water Chain

The water chain model developed for this study was based on an 8-month investigation of community water quality and practices which was presented previously (Mellor *et al.* , 2012b) and is summarized in Chapter 2. That study focused on 50 households within the communities and found significant monthly inter and intra-household water quality variability along with consistently higher levels of total coliform bacteria present at the household level compared to source water. It also found significant total coliform bacteria levels associated with the sidewalls of storage containers, on water transfer devices used to scoop water (typically a ladle or cup) and associated with participants' hands. The study also found significant bacteria regrowth in stored water containers indicating an important contributor to household bacteria levels.

Table 3.1: *Variables "owned" by the two agent types: households and children. 1 - variables that can change daily. 2 - variables that are stochastically varied over a continuous uniform distribution between minimum and maximum reported values. All values based on data collected in the communities for individual households or children. Households not surveyed take on values of their nearest neighbor. SW - surface water, CP - community piped, MT - municipal tap, WQ_i daily water quality of i^{th} household.*

Households		Children	
Variable	Range	Variable	Range
Primary water source	SW,CP,MT	Sex	M/F
Secondary water source	SW,CP,MT	Age[1]	0 - 730 d
Daily water quality (WQ_i)[1]	0-4000 cfu/100mL	ECD Status[1]	single/double case
Days have kept water[1]	0+ d	Daily growth[1] increment	-0.198 - 0.176 cm
Maximum days can keep water	1 - 14 d	Height[1]	0+ cm
Water collection interval[2]	every 1 - 10 d		
Water container cleaning interval[2]	every 1 - 365 d		
Water boiling interval[2]	every 1 - 30 d		
Daily hand-washing interval[2]	0 - 24 #/d		
Coliforms associated with hands	0 - 8,615 cfu/100mL		
Biofilm layer coliform contribution (HHS_i)	0 - 10,000 cfu/100mL		
Water transfer device coliform contribution	0 - 5,064 cfu/100mL		

Table 3.2: *Global variables used in model. All variables ranges gathered from field data. ECD - early childhood diarrhea. HAZ - number of standard deviations above or below world health organization normal values. SW - surface water, CP - community piped, MT - municipal tap*

Variable	Value or Range
Duration of Stunted Growth	240 d
Single ECD Case HAZ Reduction	-1.50 - 1.47
Double ECD Case HAZ Reduction	-2.18 - 1.93
SW Water Quality	0 - 4120 cfu/100mL
CP Water Quality	0 - 1220 cfu/100mL
MT Water Quality	0 - 500 cfu/100mL
SW Reliability	100.00%
CP Reliability	45.43%
MT Reliability	68.43%

"Narrow neck" containers were generally cleaner.

Unpublished results taken concurrently and described in detail in Appendix A.1.1 surveyed participants about water source preferences and reliability, the number of days participants kept water, the maximum number of days a household could keep their water as well as the frequency of water boiling, water container cleaning, and hand-washing. To minimize the effects of report bias, the same information was asked during caregiver interviews and daily report calendars multiple times using multiple different questions. These results are then stochastically varied over a continuous uniform distribution between the minimum and maximum reported values in the model to more realistically represent actual behavior for each respective household surveyed. Households not surveyed are then given the same characteristics as the closest household that was surveyed.

During each model "day" the water quality parameter of the i^{th} household is represented by WQ_i (cfu/100mL) and can change according to the water chain shown in Figure 3.1. For this study, WQ_i is represented by total coliform bacteria.

Initially, if a household's primary water source is operational and if a household needs water, it can collect it from the three main water sources, MT, CP or SW which have associated reliability and quality. If a household wants to collect water, but their primary water source is inoperable, they wait for some number of days. If a household cannot wait any longer (i.e. they have exceeded their "Maximum days can keep water") they then revert to a secondary water source, which is frequently of inferior quality.

Once a household has collected water, it is put into their water storage container where it may be contaminated by the biofilm layer on the inside of the container. The

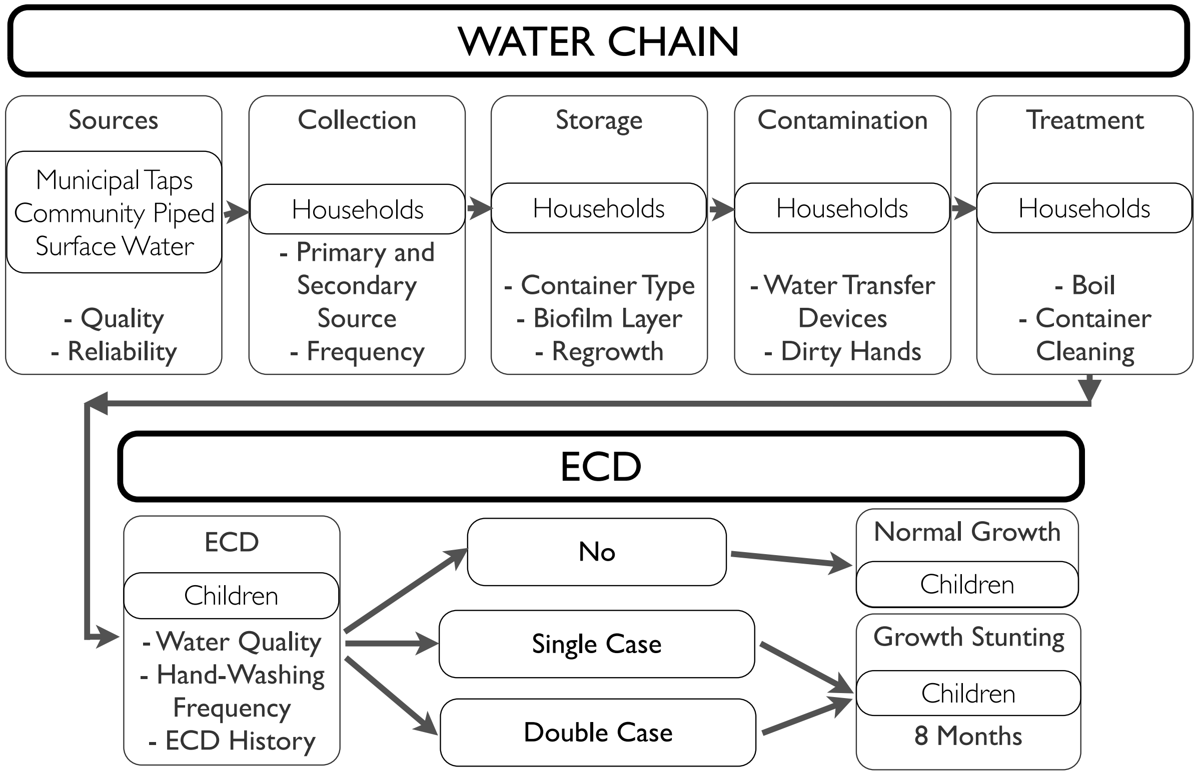

Figure 3.1: *Flow chart of ABM routines. Source water can be of three different types, municipal tap (MT), community piped (CP) and surface water (SW) with related quality and reliability. Households collect water from either a primary or secondary source with a given rate. During storage the water can be contaminated by a biofilm layer or biological regrowth which depends on container type and source water. Water can be further contaminated by water transfer devices or dirty hands for "wide neck" containers. Finally, it can be treated by boiling or water quality can be improved through container cleaning. This water chain determines WQ_i - the water quality of the i^{th} household - which in turn makes children more or less likely to get ECD. A child's propensity to get ECD can be decreased through hand-washing frequency or increased through previous ECD cases. Children then grow according to their ECD status. They experience stunted growth during "single" cases of ECD and are further stunted if they get two or more cases of ECD within 8 months.*

contamination amount is based on field measurements previously reported (Mellor *et al.* , 2012b), summarized in Chapter 2 and detailed in Appendix A.2. Likewise field measurements also found significant coliform bacteria associated with households" water transfer devices (typically cups or ladles) and hands. If a household uses a "wide neck" storage container their water can be contaminated by water transfer devices and hands as detailed in Appendix A.2. During the storage period WQ_i can increase or decrease daily as a result of bacteria regrowth or death which is a function of storage period, water source type and water container type (Mellor *et al.* , 2012b).

Households can treat their water by boiling at a frequency determined as being stochastically varied over a continuous uniform distribution between the minimum and maximum values reported during field surveys. Boiling efficiency is estimated through a literature review to be 98.57% effective in similar settings (Clasen *et al.* , 2008b; Rosa *et al.* , 2010; Clasen *et al.* , 2008a). It is modeled using a normalized distribution with SD = 0.111. Finally, households can choose to clean their water storage containers at a frequency determined by the field surveys. This reduces coliform levels by a stochastically varying (continuous uniform distribution) amount determined by field measurements of between 20 and 27%.

During each model day, WQ_i is calculated for each household as outlined above. The propensity of a child living in a given household to get ECD is based on WQ_i and a stochastic variable (continuous uniform distribution) calculated daily ranging between the low and high values of the best available dose-response literature for *E. coli* (Brown *et al.* , 2008; Jensen *et al.* , 2004) and summarized in Table 3.3.

A child can decrease their ECD risk by up to 43% if they practice optimal hand-

Table 3.3: *Daily probabilities of getting early childhood diarrhea (ECD) based on household water quality (WQ_i). Values based on literature values for E. coli and correspond to WHO guidelines on risk associated with the consumption of various water qualities.*

WQ_i	Probability of Getting ECD
0 - 1 cfu/100mL	0%
1 - 10 cfu/100mL	0.75 - 2.00%
10 - 100 cfu/100mL	0.87 - 3.00%
100 - 1000 cfu/100mL	0.94 - 3.71%
1000+ cfu/100mL	1.08 - 3.29%

washing (Curtis & Cairncross, 2003) which has been estimated to require people to wash their hands 32 times per day (Graeff *et al.* , 1993). This is modeled by taking a stochastically varying (continuous uniform distribution) number of daily hand-washing events between the minimum and maximum reported values for each household. A child's propensity to get ECD is then reduced by dividing this number by 32 and multiplying by 0.43.

Children typically do not consume water during their first months of life. This is reflected in the fact that those children cannot get ECD from the consumption of water during that period and is based on field data about child water consumption in the communities. Children in the communities receive a rotavirus vaccine which has been shown to reduce total ECD cases by 44.1% in South Africa (Madhi *et al.* , 2010). This reduced risk is used in the model. Finally, a child's future risk can be increased by a factor of 1.93 if ECD occurs during their first year of life (Moore *et al.* , 2010).

3.2.4 Child Growth

Child growth stunting is a sensitive measure of ECD incidences (Checkley *et al.* , 2008). One convenient measure of child growth are HAZ scores which, for the purposes of this work, is the number of standard deviations above or below World Health Organization (WHO) normal values (De Onis, 2006). This age and gender neutral metric is positive for children that are growing faster than normal, and negative for children whose growth is below normal.

A project entitled The Interactions of Malnutrition & Enteric Infections: Consequences for Child Health and Development (Mal-ED) has been tracking ECD incidences and child height of children under two years of age for more than two years and has accrued 3,847 child height measurements of 313 children in the immediate vicinity of the communities (Lang, 2011). That data indicate that children are born at approximately 0.84 standard deviations below WHO median values. The ABM children are therefore born according to a normalized height distribution whose mean value is -0.84 with standard deviations of 1.90 and 1.86 cm for boys and girls respectively. These standard deviations represent world average values at birth (De Onis, 2006). After birth, children follow a piecewise linear fit of standard WHO median growth curves until they get ECD (WHO, 2012).

If a child gets ECD, their growth is stunted by an amount calculated from Mal-ED results. These data indicate that during the 4-month period before and after an ECD incidence, children's HAZ scores are reduced by an average amount of 0.237 ($t(59) = 4.68$, $p < 0.001$) compared to healthy children. Furthermore, children with two or more cases of ECD within that eight-month period have their HAZ reduced by 0.424 on average more than healthy children ($t(70) = 4.91$, $p < 0.001$). These two scenarios will henceforth be called "single" and "double" ECD cases respectively. This HAZ data is incorporated into the model as outlined in Appendix A.2 .

Model results can be summarized using three main metrics. These are the median daily household water quality (WQ_i), mean ECD cases per child over the first two years of life and mean HAZ at age two (HAZ_2).

3.2.5 Statistical Methods

A chi-squared test (Kottegoda & Rosso, 2008) was performed on daily WQ_i values to compare the modeled data with field household water quality measurements. The data was divided into the following ranges: $0 - 10$, $10 - 100$, $100 - 1000$ and 1000+ cfu/100 mL for the test.

3.2.6 Behavior Space Analysis

Netlogo allows users to easily vary parameters to better understand the sensitivity of a model to those parameters and to understand how given agent behaviors might affect model outcomes. Parameters and ranges were chosen based on field measurements and are outlined in Table 3.5. For each parameter variation, the model was run for 100 different 30-year runs. This gave reasonable statistical significance while being computationally manageable. Four of the most interesting analyses are summarized below, while eleven other analyses are included in Figures A.12 and A.13.

In order to further elucidate the model's controlling parameters a large scale behavior space analysis was conducted in which the eleven model parameters deemed most likely to generate meaningful changes in HAZ_2 were simultaneously varied. These parameters were varied across ranges that generated the most interesting responses during the single parameter analysis. These parameter combinations resulted in 46,656 30-year runs with each parameter combination being run only once. Results were analyzed by comparing the varied parameter values for the top 1% of simulation runs in terms of HAZ_2.

3.3 Results

3.3.1 Model Validation

The model represents all of the essential elements of the water chain system identified in the field work. Calculated WQ_i values also reasonably reproduce the 8-months of field measurements of household water quality as can be seen with the cumulative distribution function in Figure 3.2. The chi-squared test indicates that the fit is statistically significant ($\chi^2 = 5.8116$, p = 0.121).

The average ECD cases per child for the two year period were 8.49 cases, which is consistent with a 2010 survey of African children which found a rate of 8.45 cases during the first two years of life (Walker *et al.* , 2012).

The plot of monthly mean HAZ scores in Figure 3.3 indicates a reasonable fitting of the data. In that plot, the ABM children's monthly average HAZ scores are plotted along with the Mal-ED data set. One sample t-tests indicate that the model reasonably represents the community growth curves for 22 of the 25 months (See Table 3.4).

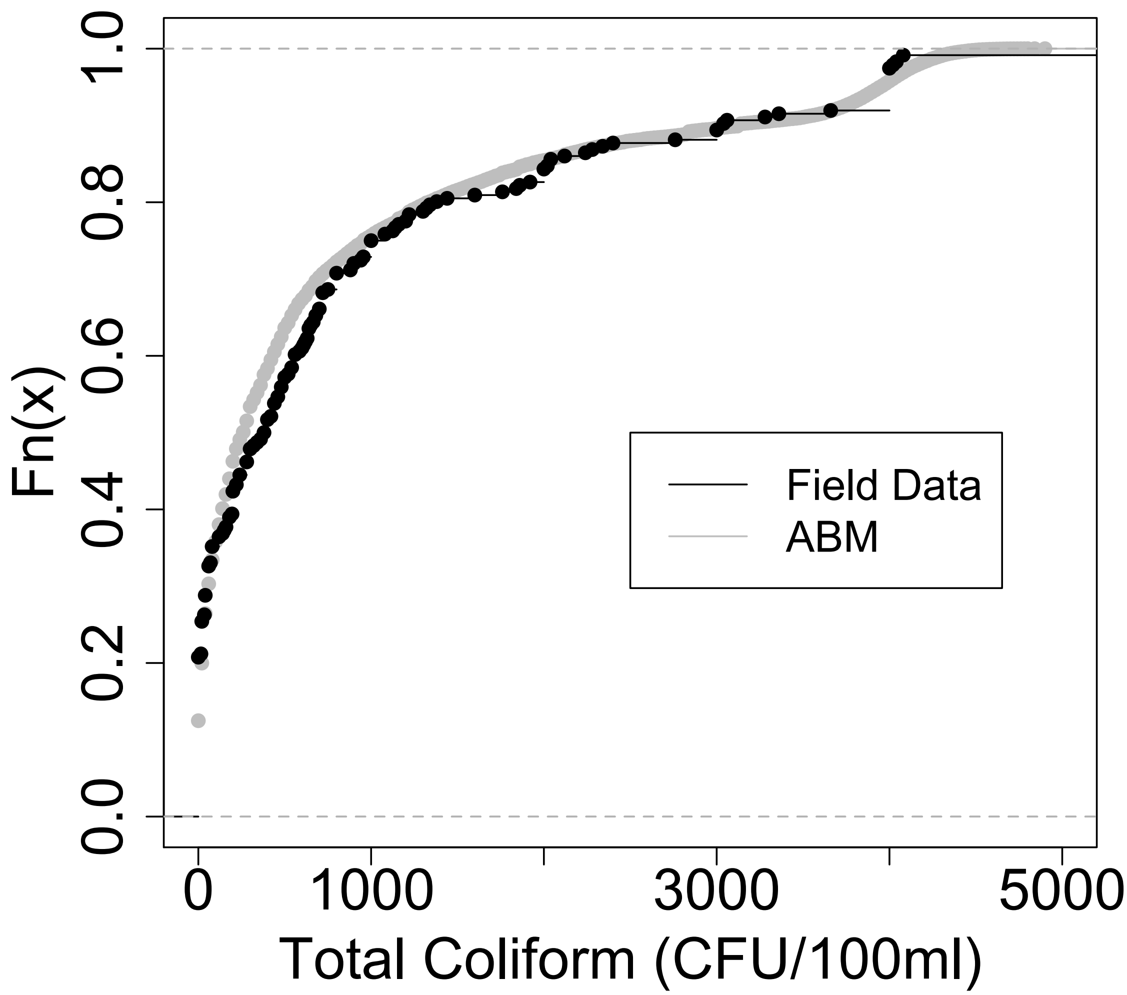

Figure 3.2: *Cumulative distribution function (Fn(x)) of 8 months of household water quality field measurements compared to discretized ABM simulated values.*

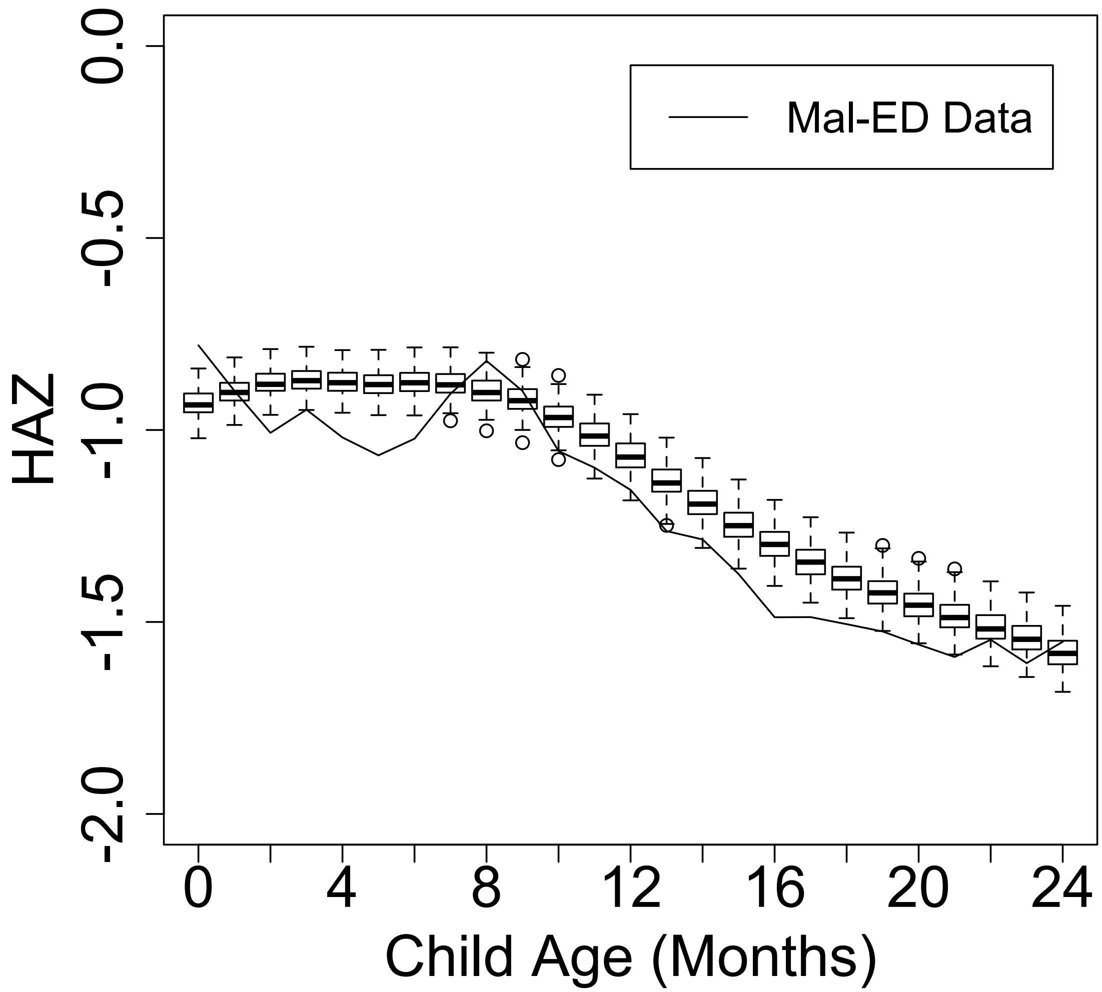

Figure 3.3: *A plot of HAZ scores vs child age. The ABM results are shown with box plots, while the average monthly Mal-ED data is given with the solid line. One sample t-tests shown in Figure 3.4 indicate that the model is accurate for 22 of the 25 months. HAZ - number of standard deviations above or below world health organization normal values.*

Table 3.4: *P-values for t-test comparing simulated and field values for child height. These p-values indicate that the model reasonably replicates field data for 22 of the 25 months.*

Month	p-value
0	0.014
1	0.971
2	0.068
3	0.286
4	0.054
5	0.019
6	0.053
7	0.735
8	0.381
9	0.776
10	0.329
11	0.331
12	0.344
13	0.133
14	0.301
15	0.201
16	0.049
17	0.135
18	0.285
19	0.363
20	0.403
21	0.382
22	0.813
23	0.653
24	0.850

3.3.2 Single Parameter Behavior Space Analysis

Results from the single parameter behavior space analysis are summarized in Figure 3.4. That figure summarizes the results of four different behavior space analyses in terms of median daily water quality, mean number of ECD cases per child over the first two years of life and mean HAZ_2. Boiling and collection intervals are in terms of those behaviors occuring every X days, where X varies from 1 to 7. The third experiment is municipal tap water quality (MT WQ) in which the municipal tap water quality was varied over the non-linear range given in Table 3.5. Finally, in the last experiment the container biofilm layer (HHS_i) was varied over the non-linear range shown in Table 3.5.

Median WQ_i varied significantly across boiling frequencies ($F = 18{,}965$, $p < 0.001$), collection frequencies ($F = 166$, $p < 0.001$), MT water quality ($F = 31658$, $p < 0.001$) and biofilm layer contribution (HHS_i) ($F = 166{,}629$, $p < 0.001$). Optimal behaviors and conditions resulted in reasonable median WQ_i in all four cases presented. However, daily water boiling and having an HHS_i of 0 cfu/100 mL resulted in the best overall median WQ_i.

Increased boiling frequency was associated with improved WQ_i. For the water collection experiment, WQ_i was better when it was collected daily and deteriorated markedly in simulation runs when households collected their water every 2 or more days. Interestingly, water quality improved slightly for houses who kept their water for more than 3 days. These two trends are due to biological regrowth and eventual death. MT water quality had a significant impact on household WQ_i, although even perfect source water quality resulted in less than perfect household quality. Biofilm layer contributions (HHS_i) proved to be the most significant factor in poor WQ_i,

Table 3.5: *Parameters and their values used in the single-parameter behavior space analysis. All parameters and value ranges used were based on field measurements. For the single-parameter behavior-space experiments, each parameter was varied over those respective ranges. Results are summarized in Figure 3.4 and in A.12 and A.13. SW - surface water, CP - community piped, MT - municipal tap*

Parameter	Single Parameter Values
MT Useage	0 - 100%
CP Useage	0 - 100%
SW Useage	0 - 100%
“Narrow Neck” Container Use	0-100
Biofilm Layer Contribution (cfu/100mL)	0, 100, 200, 300, 400, 500, 1000, 2000, 3000, 4000, 5000
Water Transfer Device Contribution (cfu/100mL)	0, 100, 200, 300, 400, 500, 1000, 2000, 3000, 4000, 5000
Slow Sand Filter	ON, OFF
SW Reliability (Operational every X Days)	1 - 7
CP Reliability (Operational every X Days)	1 - 7
MT Reliability (Operational every X Days)	1 - 7
Collection Interval (Collect every X Days)	1 - 7
Cleaning Interval (Clean every X Days)	1 - 7
Hand-Washing (Hand-washing events per day)	1 - 32
SW Water Quality (cfu/100mL)	0, 250, 500, 1000, 2500
CP Water Quality (cfu/100mL)	0, 50, 100, 250, 500, 1000
MT Water Quality (cfu/100mL)	0, 25, 50, 100, 250, 500
Boiling Interval (Every X Days)	1-7

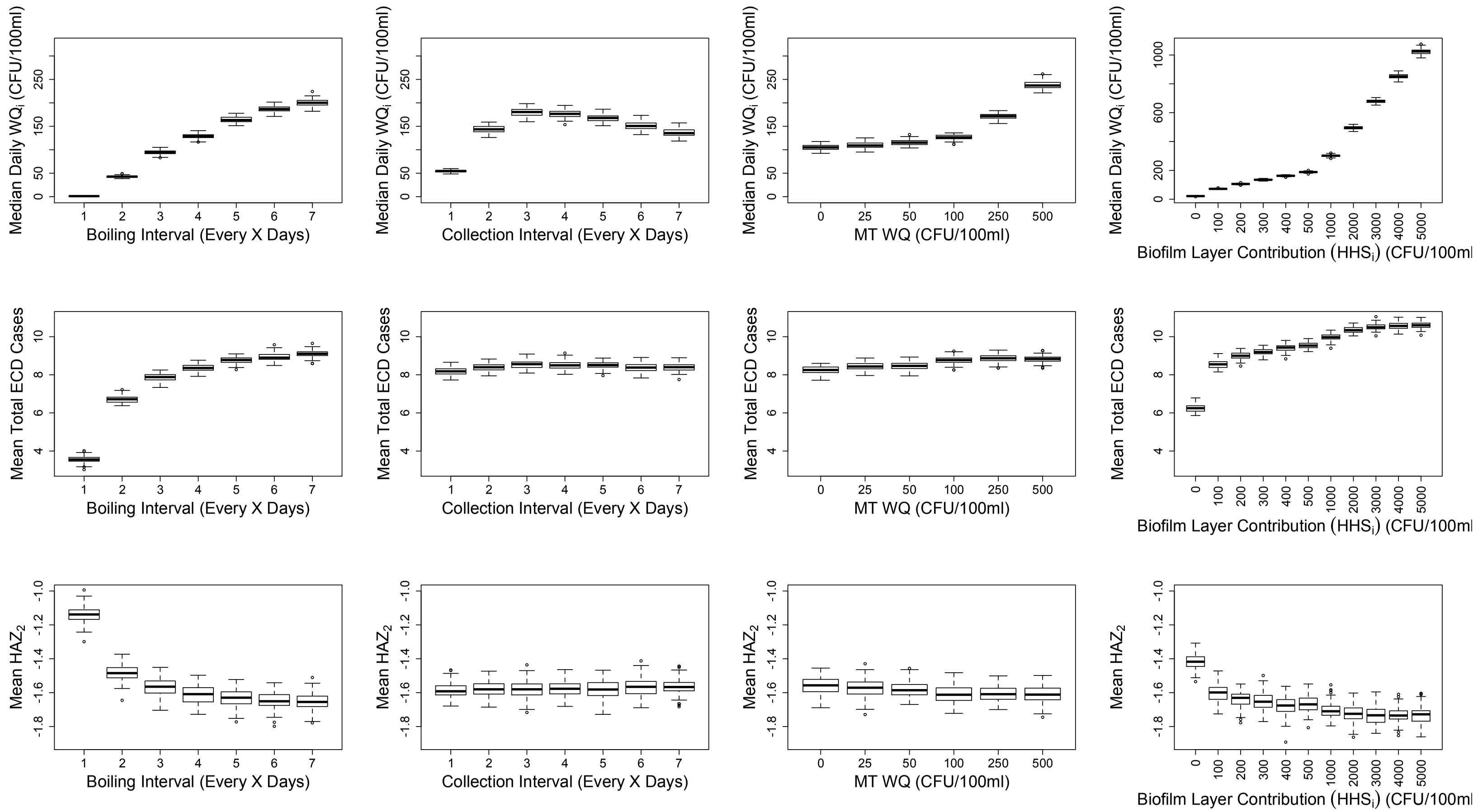

Figure 3.4: *Single parameter behavior space analysis of model summarizing the results from four different behavior space runs with median daily WQ_i, mean total ECD cases, and mean HAZ_2. The boiling and collection interval experiments are in terms of those behaviors occurring every X days. Municipal tap (MT) water quality is the water quality of the MT water system and is varied according to typical ranges found in field data. Biofilm layer contribution (HHS_i) is the amount of coliform bacteria associated with the water storage container sidewalls and is also varied across ranges typical of the field data. Results indicate that only optimal interventions (e.g. daily boiling and HHS_i = 0 cfu/100 mL) produced large reductions in growth stunting as reported by HAZ_2 values. Other variables such as daily water collection and low coliform levels in the MT water system improved water quality, but failed to decrease ECD rates or child stunting.*

especially when HHS_i was very high.

Mean ECD cases also varied statistically across boiling frequencies ($F = 1955.2$, $p < 0.001$), collection frequencies ($F = 17.061$, $p < 0.001$), MT water quality ($F = 293.96$, $p < 0.001$) and biofilm layer contribution (HHS_i) ($F = 989.82$, $p < 0.001$). However, large ECD reductions were seen in only a few cases. ECD cases were much lower during simulation runs when all households boiled their water every day compared to those who did so less frequently. Furthermore, during runs in which all households had 0 cfu/100mL of HHS_i there were fewer ECD cases. Despite WQ_i improvements seen, collection frequency and MT water quality had little impact on mean ECD cases.

HAZ_2 varied across boiling frequencies ($F = 1079.2$, $p < 0.001$), collection frequencies ($F = 12.194$, $p = 0.001$), MT water quality ($F = 46.214$, $p < 0.001$) and biofilm layer contribution (HHS_i) ($F = 472.35$, $p < 0.001$). However, most of these differences were modest and were similar to ECD results. Significant improvements in HAZ_2 scores are only seen when interventions such as boiling are done every day. Likewise, having 0 cfu/100mL of HHS_i resulted in improved HAZ_2 levels. Collection frequency and MT water quality were not strongly correlated to HAZ_2 changes.

Behavior space analyses for all other parameters are summarized in Figures A.12 and A.13 . In brief those results indicate a moderate relationship between median daily WQ_i and the percentage of houses that have "narrow neck" containers, water transfer devices coliform levels, coliform regrowth, CP water quality, the increased use of the CP and MT water systems and slow sand filter (SSF) status. These relationships translated into meaningful differences in ECD incidences and hence HAZ_2 for households with "narrow neck" containers, CP water quality and the prevalence of

CP and MT water systems. ECD rates as a function of hand-washing frequency also showed a strong correlation to ECD cases and HAZ_2. The model was less sensitive to water container cleaning intervals, SW water quality and CP and MT operational rates.

3.3.3 Multiple Parameter Behavior Space Analysis

The multiple parameter behavior space analysis provided further insight about which parameters have the most potential to improve HAZ_2 scores. Each varied parameter is listed in Table 3.6. Table 3.6 also has the values over which each parameter was varied. Alongside each of those values is the percent of runs with that value that were in the top 1% of all 46,656 runs in terms of HAZ_2. The top 1% corresponded to runs with HAZ_2 values of -0.663 or greater. This can happen when there is an average of less than one ECD case per child during those simulations. These HAZ_2 scores are notable because they are significantly lower than any single intervention from Figure 3.4 These results can be interpreted by comparing the percents for each parameter value. Large differences in the percentages corresponds to important parameters. Likewise, small differences in the percentages means that those parameters are less important. For instance, parameters such as biofilm layer contribution where 100.0% of the runs in the top 1% had 0 cfu/100mL indicate that that HAZ_2 scores are highly sensitive to it. Conversely, CP reliability is less important since 49.7% of runs in the top 1% of all runs had the CP operational every day, while 50.3% of the runs had CP only operational every week.

Based on these results it is clear that HAZ_2 scores are sensitive to container type, biofilm layer contribution, boiling frequency, MT water quality and CP water quality.

Table 3.6: *Multiple parameter behavior space analysis of ABM. Parameter and values tested along with the percent of runs for each value that were in the top 1% of all 46,656 runs in terms of HAZ_2. Large differences in these percents indicate important parameters, while small differences mean that the parameter is less important. Data indicate that container type, biofilm layer contribution, boiling interval, MT water quality and CP water quality are the most important controlling system parameters.*

Parameter	Parameter Values	Percent of Runs in Top 1%
MT Use	25%	13.9
	50%	20.8
	75%	65.3
"Narrow Neck" Container Use	0%	0.6
	50%	0
	100%	99.4
Biofilm Layer Contribution (cfu/100 mL)	0	100.0
	250	0.0
	500	0.0
Water Transfer Device Contribution (cfu/100 mL)	0	33.0
	500	32.5
	4000	34.5
Slow Sand Filter	ON	54.6
	OFF	45.4
CP Reliability (Days per Week Operational)	1	49.7
	7	50.3
Collection interval (Every X Days)	1	7.7
	2	12.8
	3	22.9
	7	56.5
Cleaning interval (Every X Days)	1	54.0
	7	46.0
CP Water Quality (cfu/100 mL)	0	69.4
	100	19.9
	500	10.7
MT Water Quality (cfu/100 mL)	0	91.0
	100	9.0
Boiling interval (Every X Days)	1	69.4
	2	18.6
	7	12.0

Conversely, the water transfer device contribution, SSF status, CP reliability, collection frequency and cleaning frequency were not as important. Most importantly, these results suggest that optimal ECD reductions might be realized even when less important parameters are sub-optimal and that highly effective intervention combinations can reduce ECD to very low levels.

3.4 Discussion

This study has described the development of a novel agent-based model informed by four years community data and its ability to dissect the complex human/engineered/-natural system that leads to poor household water quality and ECD. Household boiling frequency, source water quality, water container type and biofilm layers are all potential intervention areas that might lead to large reductions in ECD. However, the model indicates that these interventions must be optimally implemented before significant improvements can be attained. Furthermore the model suggests that, intervention combinations, when optimally implemented can effect large reductions in ECD even when other areas remain unimproved.

The results indicate that although single interventions can significantly reduce risk, intervention combinations can reduce it much further. This is especially notable since the model indicates that only the most important contributors need to be minimized to realize this goal. This work is supported by the work of Eisenberg *et al.* (2007), who found that all significant transmission pathways must be stopped to effect maximum benefits. The results herein also show how much the combined effects of multiple interventions might be able to reduce ECD rates and what interventions in particular are most important. In addition, this model has its foundation in field data from two well-studied communities. The model does differ somewhat from previous results that looked at the effectiveness of multiple interventions. For instance, the Fewtrell meta-analysis (Fewtrell *et al.* , 2005) found multiple interventions to be less effective than some other individual interventions including handwashing and household water treatment. However, as the authors state, it is likely that those multiple intervention trials looked at sub-optimal implementation.

The behavior space analyses summarized in Figure 3.4 provide an interesting insight into the system complexities. In the case of boiling frequency, median water quality increases at a near linear rate, while ECD cases and HAZ_2 follow a highly non-linear trend. This is due to the non-linear dose-response curve. This diagram also points to the difficulty in implementing water boiling campaigns especially in regions where household water treatment is rarely and inconsistently practiced (Rosa & Clasen, 2010) and in any community where behavior change is challenging (Mosler, 2012). Similar results were also found by Enger *et al.* (2012b) who emphasized the importance of compliance for household water treatment interventions.

The collection frequency simulations point to the potential importance of biological regrowth and other contamination sources in such communities (Mellor *et al.* , 2012b). This analysis found that although household water quality was much better for houses that collected water everyday, this improvement did not directly translate into a large decrease in ECD cases or HAZ_2 scores. This might be why researchers have found mixed results on diarrhea rates when studying water system reliability. In South Africa Majuru *et al.* (2011) found that the health gains of new water systems were largely lost if they were unreliable, while Lee & Schwab (2005)'s meta-analysis suggested that risk assessment of diarrheal diseases due to system failure is tenuous.

Improving MT water quality led to significant improvements in household water quality in the model. However, this improvement again did not lead directly to large ECD reductions or improvements in HAZ_2. MT improvements would have been more effective at improving ECD rates if all residents used this system. The fact that improved source water quality does not necessarily lead to large reductions in ECD rates is well-known in the literature (Fewtrell *et al.* , 2005; Clasen *et al.* , 2007). The results presented here may explain why improving source quality does not always drastically reduce ECD rates.

The biofilm layer contribution experiments showed the largest variation in household water quality in the model. These variations led to significant variations in ECD rates and HAZ_2 scores. This is one indicator as to why point-of-use ceramic filters have proven to be effective at reducing ECD rates (Hunter, 2009) worldwide and why safe water systems that prevent biological layer formation have improved water quality in South Africa (Potgieter *et al.* , 2009). The container cleaning experiment results are given in Figure A.12 . They do not predict large improvements because of the measured ineffectiveness of container cleaning in the communities. It is unfortunate that container cleaning is not more effective at removing biological layers in these communities and is an obvious area for improvement. More consistent chlorination should also reduce biological layer development.

The multiple parameter analysis added further insight into the complex system by elucidating the most important controlling parameters. It is these parameters that might, if properly addressed, lead to the largest ECD reductions in the communities. As was seen in the case with the single parameter experiments, biofilm layers and boiling frequency were both important parameters. In addition, the use of "narrow neck" containers provided important protection against ECD. These containers usurp the need for water transfer devices, have generally less biological regrowth (Mellor *et al.* , 2012b) and are less likely to be contaminated by fingers. This finding is supported by previous researchers who have likewise seen some improvement with narrow neck containers in Pakistan (Jensen *et al.* , 2002) or who have found that covered water storage containers in Zimbabwe are generally cleaner (Mazengia *et al.* , 2002).

The importance of MT and CP source water quality is somewhat surprising given that most researchers have found that source water protection does not always lead to substantial reductions in ECD rates (Fewtrell *et al.* , 2005). However, other researchers in Mozambique have shown an association between source and household water quality (Cronin *et al.* , 2006).

The modeled results presented herein are likely reasonable representations of results obtainable in the field. First of all, the water chain model described in Figure 3.1 represents all elements of the system as measured in field work and reproduces WQ_i values measured in household water. This water chain model was loosely based on the F-diagram (Wagner & Lanoix, 1958), but goes far beyond it in terms of the system complexity and is fully quantified using field data (Mellor *et al.* , 2012b).

Secondly, given the water quality data, and the dose-response relations used, the average ECD rate of 8.49 cases during the first two years is consistent with previous studies (Walker *et al.* , 2012). Furthermore, the average yearly ECD rates for 0-5, 6-11 and 12-24 month old children are 2.1, 4.4 and 5.1 which is statistically equivalent to the Walker study for those same age ranges in Africa (Walker *et al.* , 2012). The relative risk associated with daily boiling from this study, 0.42, is statistically identical to the relative risk of 0.65 (0.39 - 0.94) seen by others for household water treatment

(Fewtrell *et al.* , 2005). The results are closer if one assumes more irregular boiling in the ABM. Furthermore, the relative risk associated with the increased use of MT was 0.85 in this study which compares favorably to the 0.94 (0.65 - 1.35) seen previously for a community water connection (Fewtrell *et al.* , 2005).

Lastly, the stunting seen in the communities is consistent with that seen in a similar Brazilian study (Moore *et al.* , 2010) which found stunting to decrease by 0.31 for ECD cases lasting less than 7 days and 0.59 for ECD cases lasting 7 to 13 days. The ABM child growth curve shown in Figure 3.3 does an accurate job of recreating the Mal-ED data. In both cases children start off stunted, but remain at approximately the same level during the first 6 to 8 months of life. This is likely due to the fact that those children are getting ECD at lower rates because many are not consuming water daily. The lower rates for children under 6 months old are seen in previous meta-analyses of African children (Walker *et al.* , 2012).

Although the model is based on data obtained from the two South African communities the risk factors and proposed interventions are generalizable to other similar settings in the developing world. First of all, the water sources used are typical of those found in other parts of Africa (Thompson, 2001) and other developing regions. Secondly, the community's source water quality is likewise typical. The recontamination of water between source and household is well documented in the literature for many parts of the world (Wright *et al.* , 2004) and the sources of recontamination are similar to those found in previous studies in Honduras (Trevett *et al.* , 2005) and Tanzania (Pickering *et al.* , 2010b). Finally, the water and sanitation behaviors and practices of the residents have likewise been observed in a number of previous studies (Thompson, 2001; Rosa & Clasen, 2010).

Although the model is well validated, the use of the *E. coli* dose-response relations summarized in Table 3.3 to predict the dose-response relationships for total coliform bacteria is sub-optimal. However, total coliform bacteria is a indicator of bacterial regrowth (LeChevallier, 1990) and inadequate water treatment (EPA, 1989) two of the critical components of the model. Furthermore, the presence of total coliform bacteria can indicate that other harmful bacteria may be present (EPA, 1989). The use of the discretized risk categories in Table 3.3 based on total coliform concentration is a reasonable approach because it is likely that water with high total coliform concentrations is somewhat more likely to have high levels of pathogenic bacteria. Furthermore, the sensitivity analysis given in Figure 3.5 indicates that linear variations of the dose-response relation does not affect the overall shapes of the HAZ_2 output data and hence has little impact on the qualitative conclusions reached in this analysis. Finally, the water chain framework developed for this model can be easily adapted for other pathogens by future researchers.

It is also true that nutritional intake and acquisition of protective immunity against pathogens that cause ECD (i.e. through breast-feeding) are important and are not fully reflected in this model. One area for further study would be to incorporate the currently evolving understanding of the relationships between malnutrition and immunity (Korpe & Petri, 2012).

Although three susceptibility parameters (hand-washing reductions, rotavirus vaccination status and the doubling of ECD susceptibility for previously infected children) are based on other reviews, the susceptibility to get ECD is based on household drinking water quality. Since these three parameters are applied uniformly to all children irrespective of their water quality, changing these parameter values only leads to uniform linear changes in HAZ scores and have no impact on the main conclusions of this

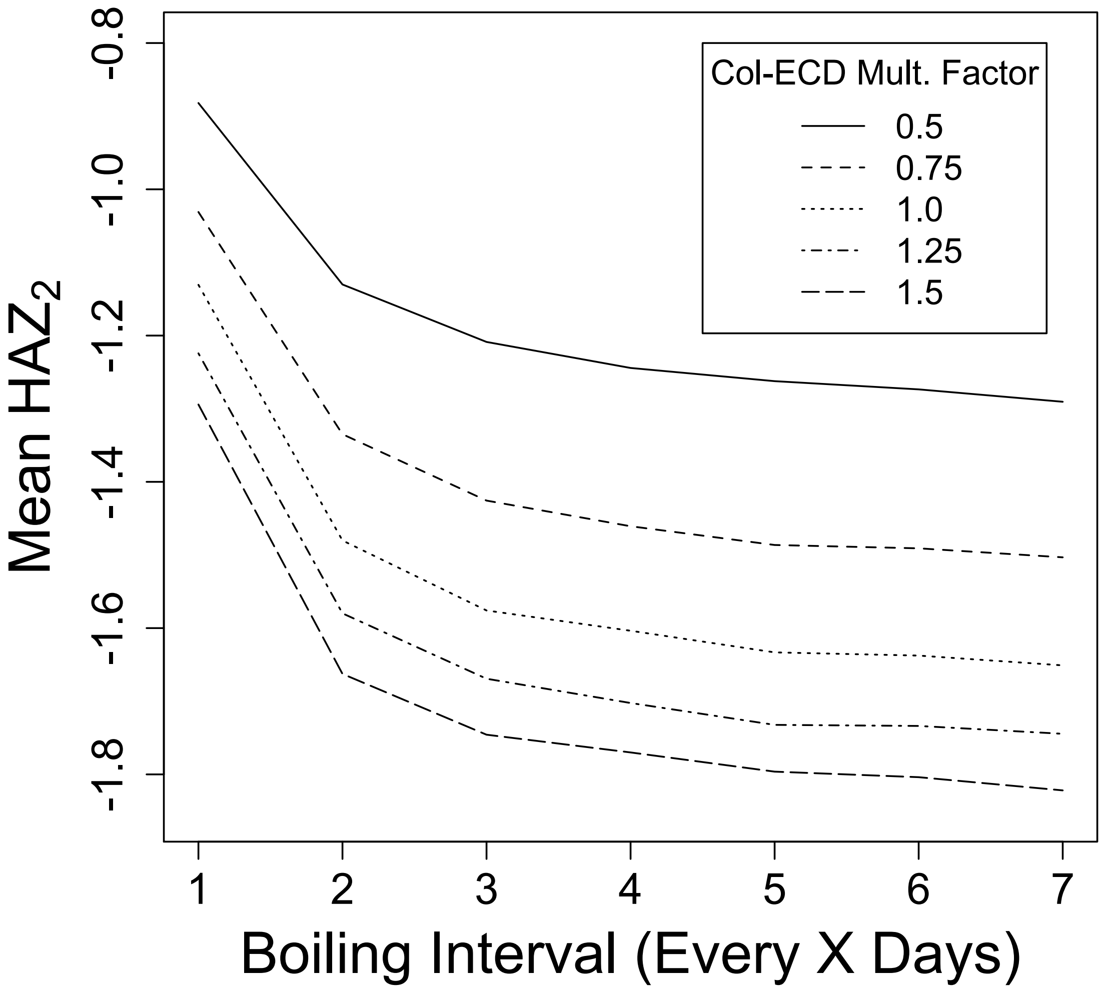

Figure 3.5: *Mean HAZ_2 scores versus boiling frequency for five different coliform-ECD dose response function multiplicative factors. Results indicate that although HAZ_2 is sensitive to the multiplicative factor, the overall conclusions of the model would be identical regardless of that factor's value.*

study. This is seen in the sensitivity of the model to hand-washing frequency which is documented in Figure A.12 - the other parameters would perform similarly.

It is possible that the near doubling of ECD cases for children who had ECD in their first year of life could be either due to particularly poor environments for some children or due to inherent changes to a child's physiology (i.e. innate immunity or alteration of gut flora). However, the 1.93 value is based on research that controlled for household size, sanitation type, education level of mother, weaning age and birth date (Moore *et al.* , 2010). It is therefore more likely to represent the changes in a child's physiology. However, we conducted a sensitivity analysis of this parameter over a likely range which is shown in Figure 3.6. The most likely range for that parameter (1.93 to 1.5) indicates that the model is modestly sensitive to that parameter.

The ABM can be used to guide policies and community interventions. For instance, it allows one to identify the "tipping points" at which certain levels of compliance or intervention effectiveness might vastly reduce ECD rates.

Next, the ABM can be used to quickly and easily test multiple hypotheses about the effectiveness of different interventions or intervention combinations. For instance, it can be used to model ECD reductions from implementing a household ceramic water filter intervention using field data about declining microbiological effectiveness, realistic filter usage and breakage rates. A willingness-to-pay for improved water quality and water and sanitation knowledge diffusion could also be implemented. Using the model in this manner can save time and money while providing the most effective interventions for communities.

Next, the geo-spatial aspect of the model enables researchers to identify key areas of the community that might require additional attention allowing more targeted

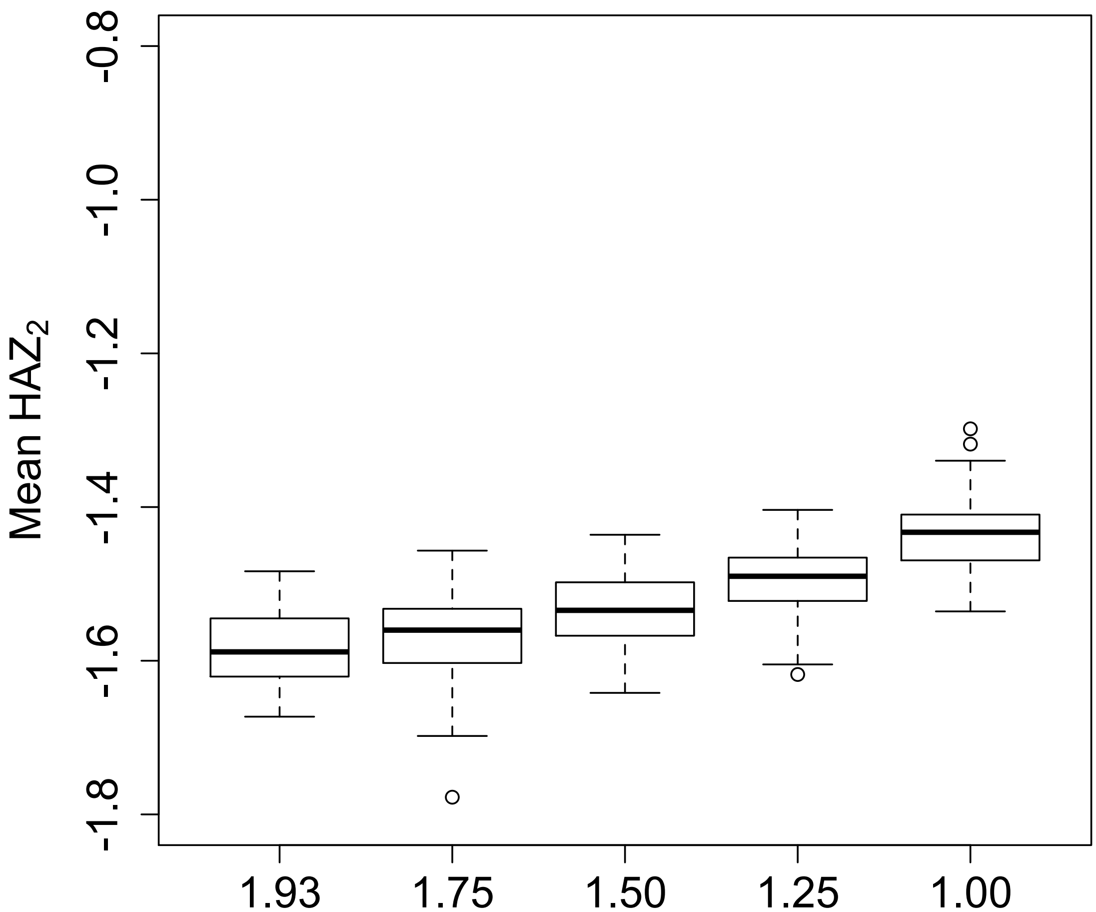

Figure 3.6: *A sensitivity analysis of the model to the parameter that nearly doubles ECD incidences after children have an ECD case during their first year of life. This analysis indicates that HAZ_2 is modestly sensitive to this parameter over the most likely range (1.93 to 1.5).*

interventions for the most vulnerable. Finally, the ABM is already proving useful as it guides university researchers as they plan upcoming interventions.

CHAPTER 4

The Sustainability of a Ceramic Filter Intervention

This study will be submitted in the early summer of 2013.

Mellor, J.E., Abebe, L., Ehdaie, B., Smith, J.A., Dillingham, R.A. (2013). "Modeling the Sustainability of a Ceramic Filter Intervention in Limpopo Province, South Africa", In Preparation.

4.1 Introduction

As was discussed in Chapter 2, water frequently becomes contaminated after collection but before consumption in many developing world countries (Wright *et al.* , 2004). This is why many have advocated for the use of point-of-use water treatment devices as a means of improving health (Clasen, 2010). Biosand filtration (Tiwari *et al.* , 2009), solar disinfection, and chlorination (Arnold & Colford, 2007) have all shown promise as means of improving household drinking water quality. Ceramic water filters are one such technology that can be produced in local communities using methods and materials that do not need to be imported. They have been shown to be a highly effective means of removing *E. coli* and other pathogens in controlled environments (Brown & Sobsey, 2010) and are typically impregnated with colloidal silver (Oyanedel-Craver & Smith, 2008). They have been shown to be effective at removing *E. coli* in the field (Kallman *et al.* , 2011) and at reducing ECD incidence (Fewtrell *et al.* , 2005).

Despite this promise, researchers have recently suggested that the evidence in support of point-of-use treatment technologies might be subject to recall bias since few studies have been blinded (Schmidt & Cairncross, 2009). Other researchers have found that factors including duration of follow-up and blinding were significant predictors of intervention effectiveness and that point-of-use water treatment device interventions may decline in effectiveness over time (Hunter, 2009). Enger *et al.* (2012a) used a quantitative microbial risk assessment (QMRA) model to find that there are diminishing returns for improved log reduction efficiency in point-of-use water treatment devices when they are not used consistently.

Two studies have been done recently to understand realistic water filter usage in the field. In the first paper Brown *et al.* (2009) found a near linear decrease in use of the filters of approximately 2% per month. They also found that the odds ratio for using a filter was 1.7 when study participants were collecting surface water compared to 0.56 when using ground water which is of presumably better quality. A second study by Casanova *et al.* (2012) found that study participants were almost twice as likely to use their ceramic water filter when there was *E. coli* present in the water. They likewise found that those with tap water were less likely to use the filters compared to those who used well water exclusively.

A final component essential for long-term sustainability is a willingness-to-pay (WTP) for new water filters after a filter breaks. Given that more than $\sim 12\%$ of filters can break over the course of a year (Brown *et al.* , 2009), it would be highly desirable to have replacement filters available for purchase. However, it is unclear how much households might be willing-to-pay for new filters (especially if they got them for free initially) and how the availability of filters for purchase might affect ECD incidences.

Given the questions surrounding the ability of ceramic water filters or any other point-of-use water treatment technology to effectively reduce ECD rates in the long term, there is a clear need to better understand the complexities of point-of-use water treatment technologies in a realistic setting. Therefore, the goal of this project is to investigate the role of factors affecting the imperfect use of ceramic water filters in preventing early childhood diarrhea. Specifically, the following factors were investigated to understand their relationship to household water quality, ECD rates and child growth stunting:

- Filter prevalence
- Filter usage
- Effects of measured declines in microbial effectiveness over time
- Filter breakage percent
- Filter breakage date
- Filter microbial effectiveness
- Linear decreases in usage over time

- WTP for new filters
- Perceptions of water quality and filter usage

This study is based on field research carried out by L. Abebe and B. Ehdaie as part of a ceramic filter intervention assessment they carried out between 2009 and 2012 in which they asked participants about filter usage and measured microbial effectiveness over time as well as WTP for new water filters. This study therefore helps implementing agencies improve ceramic water filter interventions, attempts to answer open questions in the literature (Lantagne *et al.* , 2006) and also demonstrates the adaptability of the ABM described previously (Mellor *et al.* , 2012a) to understand the complexities of disparate interventions.

4.2 Methods

As laid out in the following sections, L. Abebe and B. Ehdaie led the effort to collect the microbial effectiveness and WTP data used for the study over a three year period. As an additional consistency check, results were compared to data from E. Kallman and V. Oyanedel-Craver's work in Guatemala. These data and appropriate subroutines were then incorporated into the ABM developed in Chapter 3 to answer the research questions posited in Section 4.1 using single and multi-parameter behavior space analyses.

4.2.1 Field Methods

In 2009, L. Abebe led a team of Univen and UVA researchers to recruit approximately 93 HIV positive recruits to participate in a study to determine the ability of ceramic water filters to improve drinking water quality and reduce diarrhea in that particularly vulnerable population. Two groups were randomly assigned to either a treatment or control group. The treatment group was given ceramic water filters at study inception while the control group got filters after the year-long study was complete.

At enrollment, the influent and effluent water was tested using the standard membrane filtration protocol for total coliform bacteria described in Section 2.2.4. Influent water was take either from the upper reservoir, from stored water that was about to be filtered or from the household's current water source. The effluent was taken from the lower reservoir spigot. Similar sampling was then carried out at the conclusion of the main study in 2010 and during the summer of 2012 by B. Ehdaie. These data therefore provides longitudinal follow-up at inception, year one and year three.

Both L. Abebe and B. Ehdaie also surveyed participant attitudes about the filters and their use of them which was used in the model development and behavior space analysis. B. Ehdaie also conducted a WTP survey using the Bidding Games methodology (Wedgwood & Sanson, 2003) in 2012.

As a consistency check and to demonstrate the ability of the ABM to be generalized to other countries and regions, data gathered previously (Kallman *et al.* , 2013) was likewise utilized. The goal of that project, which is also described in Chapter 5, was to assess the long-term sustainability of a ceramic filter intervention and to compare the microbial effectiveness of point-of-use chlorination, ceramic water filters and a silver-impregnated silver disk placed in the lower reservoir. Using the protocol outlined in Section 2.2.4 they measured water quality in the summer of 2009, January 2010 and the summer of 2010.

4.2.2 Microbial Data Analysis

Each ceramic filter influent and effluent measurement was translated to a log removal value for each household so that measurements for individual households could be compared across the three sampling periods for the South African data. 35 household measures of the enrollment log reduction values were considered to be of adequate quality to include in the subsequent analyses. Even so, after enrollment, the number of participating households declined in the South African cohort. This left a number of missing data values. To rectify this, a standard multiple imputation technique (Rubin, 1978) using IBM SPSS Statistics software was used to fill in the missing log reduction values. The resulting complete data set has identical means, variability and regression parameters as the original data.

Linear piecewise fits were made between enrollment at year zero, end-of-study (year one) and follow-up (year three) for each participating household. These 35 fits are shown in Figure 4.1. It is likely that the biofilm layers on the inside of water storage containers are leading to much of the degradation of water quality seen in that figure, although the sampling method used could also be a factor. This occurrence becomes more common with filter age. The median log reduction value decreased from 2.92 at study inception to 1.63 after the first year and to 0.42 after three years.

The Guatemalan data was translated into log reduction in a likewise manner except that it was of sufficient completeness so that the multiple imputation technique was not needed. Linear piecewise fits were also done for the 20 households included in that study (data now shown). However, the midpoint measurement for that data was at approximately day 210 and the last measurement was made at approximately day 365.

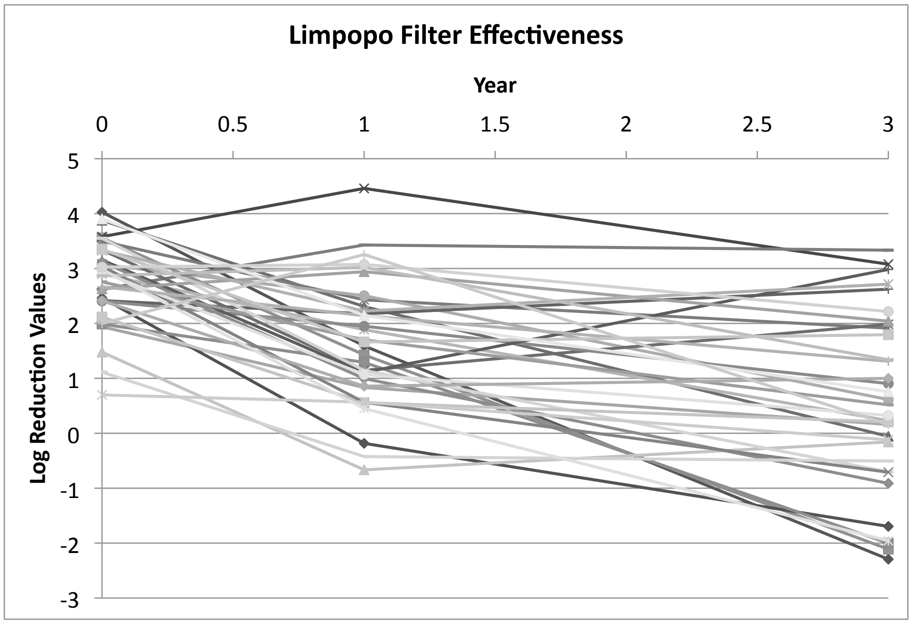

Figure 4.1: *Filter effectiveness over the three year measurement period. Missing values were filled in using standard multiple imputation techniques.*

4.2.3 Modeling Approach

Basic Routine

The ABM model described in Section 3.2.2 was modified to simulate the introduction of ceramic water filters into Tshapasha and Tshibvumo. The basic routine is meant to simulate a realistic water filter campaign introduced in the communities and is based on collected data. In this case, the filters would first be introduced for free to a percentage of the communities who would use them for the first two years of their child's life. It is assumed for the purposes of this model that 410 children are born on the same day they receive their filters. This is an average of one child per house. At run inception, each household is first randomly assigned one of the filter microbial effectiveness curves shown in Figure 4.1. On each model day the households can collect and store water, clean their water storage containers and wash their hands as they do in the previous model with WQ_i values coming from the Collection Sub-Routine shown in Figure A.7. If they have a filter and if it is not broken, each household can then use their filter. The filter effectiveness for each day is computed from that household's microbial effectiveness curve and the WQ_i increases or decreases as appropriate. This new WQ_i is the water that the child consumes on that day and the resulting potential for getting ECD and the stunted growth is calculated as before (Section A.2).

This routine was used to understand the effects of the measured declines in filter microbial effectiveness, filter prevalence and usage. This was done by keeping most values static while varying the parameter of interest with Netlogo's behavior space analysis tool. The default values are shown in Table 4.1. Filter prevalence is the percent of households in the communities with a ceramic water filter. Filter usage is the percent of time that households use a water filter if they have one. Breakage percent is the percent of filters that break during the two years. Filters have an equal chance of breaking on any model day for the basic routine.

Table 4.1: *Basic routine default values and the ranges used in the behavior space analysis.*

Parameter	Default Value	Range of Values in Behavior Space Analysis
Filter Prevalence	100%	0 - 100%
Filter Usage	90%	0 - 100%
Breakage Percent	20%	0 - 100%

Additional Routines Tested

This basic routine was modified to study several other important aspects of water filter use.

The first experiment was to determine how microbial effectiveness impacts outcomes. This was done by replacing the microbial effectiveness curves with static removal percentages that are the same for all households. Effectiveness was varied from 1 to 5 log removal.

Experience suggests that the declining microbial effectiveness seen in Figure 4.1 can be reversed if the lower reservoir is cleaned throughly. To simulate this, household microbial effectiveness declines as usual except when they clean their storage containers. At this point, their filter's microbial effectiveness reverts to day one levels and again follows their microbial effectiveness curves until the next cleaning day. Cleaning interval was varied from 1 to 730 days.

A suggestion in the literature is that usage of filters declines linearly over time at a rate of about 2% per month. To investigate the effects this might have, all household usage percentages were decreased at a linear rate from a 90% starting value.

If a filter broke early in a child's life, it would likely not be an effective ECD reduction tool. Therefore breakage date was also studied by having all filters break on the same date. This was analyzed in conjunction with breakage rates.

As discussed in the introduction, there is evidence to suggest that filter users are fairly adept at knowing when their water is contaminated and are more likely to use the filter in such circumstances. To model this effect, all simulated households are 2.05 times as likely to treat their water if it is above a given threshold value (Casanova *et al.* , 2012). Since this scenario is highly dependent on baseline filter usage, the two parameters were varied concurrently for this experiment.

Given that filter breakage is a common problem with any ceramic filter intervention and that sustainability is an important component of any development project, there is a need to study how a community's health outcomes change with willingness-to-pay for a new filter if their filter breaks. To simulate this, each household was assigned a willingness-to-pay (WTP) in South African Rand[1] based on household survey data. Then, if a filter breaks, a household can purchase a new filter if the purchase price is equal to or less than their WTP for a new filter. An important co-variate is the breakage percentage which is varied concurrently.

Table 4.2: *Other parameter values used in additional behavior space analyses. All parameter ranges are based on values typically found in this study or by previous researchers.*

Parameter	Range of Values in Behavior Space Analysis
Filter Microbial Effectiveness	10^{-5}, 5×10^{-5}, 10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3}, 10^{-2}, 5×10^{-2}, 10^{-1}
Cleaning Interval	Every 0 - 730 days
Yearly Usage Decline	0 - 100%
Breakage Date	Day 0 to 730
Threshold Water Quality	0, 0.5, 1, 5, 10, 50, 100, 500, 1000, 2000 CFU/100mL
Willingness to Pay	20, 30, 50, 70, 80, 100, 150, 200, 250, 300, 500 South African Rand

Multiple Parameter Behavior Space Analyses

As a final assessment of the system complexities two multi-parameter behavior space analyses were conducted. In the first and second cases the parameters were varied as indicated in Table 4.3 and 4.4 respectively. The data was analyzed using cumulative distribution functions (CDFs) and normalized histograms. The normalized histograms compare the percent of runs with ECD cases in a given range for each parameter value tested.

[1] $1 United States Dollar = 8.9 South African Rand

Table 4.3: *First Multiple Parameter Behavior Space Analysis*

Parameter	Range of Values in Behavior Space Analysis
Filter Microbial Effectiveness	10^{-5}, 5×10^{-5}, 10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3}, 10^{-2}, 10^{-1}
Breakage Date	Day 0 to 730 by 90 day increments
Filter Usage	0, 20, 40, 60, 80 and 100%
Filter Prevalence	0, 20, 40, 60, 80 and 100%
Breakage Percent	0, 20, 40, 60, 80 and 99%
Yearly Linear Usage Decline	0, 25, 50, 70, 90 and 100 %

Table 4.4: *Second Multiple Parameter Behavior Space Analysis*

Parameter	Range of Values in Behavior Space Analysis
Breakage Date	Day 180 to 730 by 180 day increments
Filter Usage	25, 50, 75 and 100%
Filter Prevalence	25, 50, 75 and 100%
Breakage Percent	0, 20, 60 and 99%
Yearly Linear Usage Decline	0, 25, 50, 75%
Threshold Water Quality	10, 100, 500 and 1000 CFU/100mL
Cleaning Interval	1, 30, 180 and 365 Days
WTP for New CWF	20, 50, 80, 100, 200, 500 South African Rand

4.3 Results

Overall, results indicate that the technical efficiency is just one factor in the ability of ceramic water filters to improve water quality, reduce ECD cases and improve HAZ_2 scores.

4.3.1 Basic Routine

The basic routine included analyses of several relevant parameters important to the ability of ceramic water filters to improve health including filter prevalence, usage and microbial effectiveness.

As a first consistency check, the model was run using data from both Guatemala and South Africa. Results are shown in Figure 4.2. Although there were statistically significant differences between the two datasets in terms of mean daily water quality, 266.3 vs 260.0 CFU/100mL ($t(1987.809) = 7.1655$, $p < 0.001$), median daily water quality, 4.04 vs 5.44 CFU/100mL ($t(1998) = 219.6026$, $p < 0.001$), ECD cases, 4.40 vs 4.95 ($t(1998) = -48.1445$, $p < 0.001$) and HAZ_2, -1.09 vs -1.12 ($t(1994.889) = 13.361$, $p < 0.001$), these differences were minor.

As can be seen in Figure 4.3 the data do indicate clearly that the changing microbial effectiveness seen in Figure 4.1 has a significant negative effect on the outcome variables since effectiveness decreases markedly over two years in most cases. The difference between runs with changing versus constant (i.e. day 1) microbial effectiveness are as follows: mean daily water quality, 259.8 vs 109.5 CFU/100mL ($t(1000.851) = 163.9137$, $p < 0.001$), median daily water quality, 5.37 vs 0.23 CFU/100mL($t(1582.914) = 219.6026$, $p < 0.001$), ECD cases 4.92 vs 2.70 ($t(1981.29) = 209.8923$, $p < 0.001$)

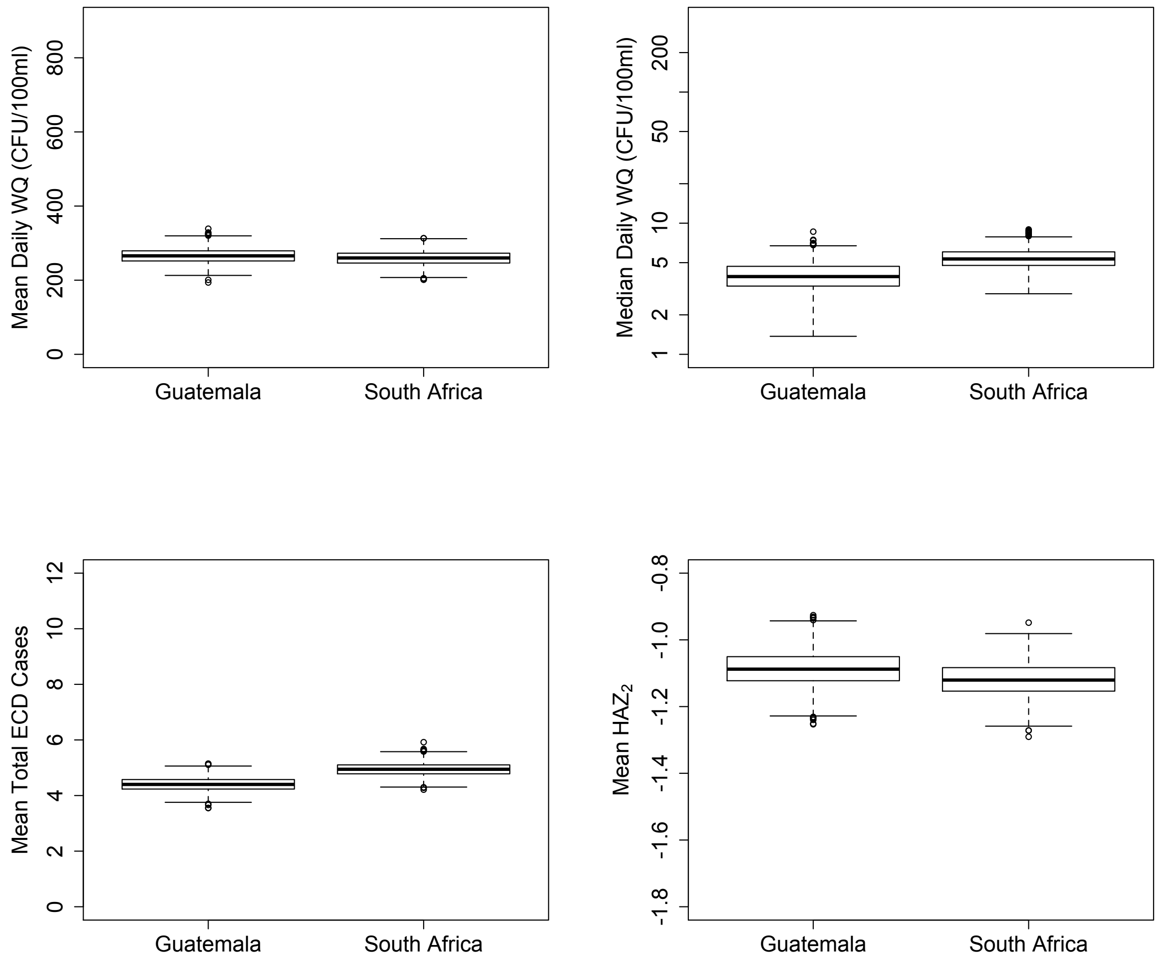

Figure 4.2: *Plots showing the mean and median daily water qualities, the mean total ECD cases and* HAZ_2 *to compare the South African and Guatemalan longitudinal microbial effectiveness data sets. Results indicate that there is little difference between the two countries and that the South African model is flexible enough to use data from other communities. The South African data will be used for the remainder of the analyses.*

and HAZ_2 -1.12 vs -0.91 ($t(1998) = -89.7681$, $p < 0.001$).

The percentage of community members with a CWF had a large effect on the outcome variables. Mean water quality ($F = 385420$, $p < 0.001$), median water quality ($F = 58994$, $p < 0.001$), ECD ($F = 185068$, $p < 0.001$) and HAZ_2 ($F = 48481$, $p < 0.001$) all declined significantly. Between 0 and 100% prevalence, mean daily water quality declined from 619.5 to 259.5 CFU/100mL, median daily water quality likewise went from 122.8 to 5.39 CFU/100mL, ECD cases declined from 8.43 to 4.95 and HAZ_2 increased from -1.50 to -1.12. The declines were linear for mean water quality, ECD incidence and HAZ_2 while they were log-linear for median daily water quality.

Even when all community members have filters, the percent of time that they use them has a large influence on the outcome variables as shown in Figure 4.5. Mean water quality ($F = 181596$, $p < 0.001$), median water quality ($F = 39394$, $p < 0.001$), ECD cases ($F = 274908$, $p < 0.001$) and HAZ_2 ($F = 63840$, $p < 0.001$) all declined significantly. Mean water quality deteriorated from 624.3 to 242.7 CFU/100mL, median water quality went from 126.0 to 4.04 CFU/100mL, while ECD cases went from 8.48 to 4.57 and HAZ_2 scores increased from -1.51 to 1.06 as usage varied from 0 to 100%.

4.3.2 Additional Routine Results

Theoretical changes in microbial removal efficiency had a significant effect on the outcome variables with mean water quality ($F = 30080$, $p < 0.001$), median water quality ($F = 1476388$, $p < 0.001$), ECD cases ($F = 43901$, $p < 0.001$) and HAZ_2 ($F = 26040$, $p < 0.001$) as seen in Figure 4.6. There was a distinct non-linearity around 10^{-3} reduction. Removal efficiencies greater than that did not have a large effect on

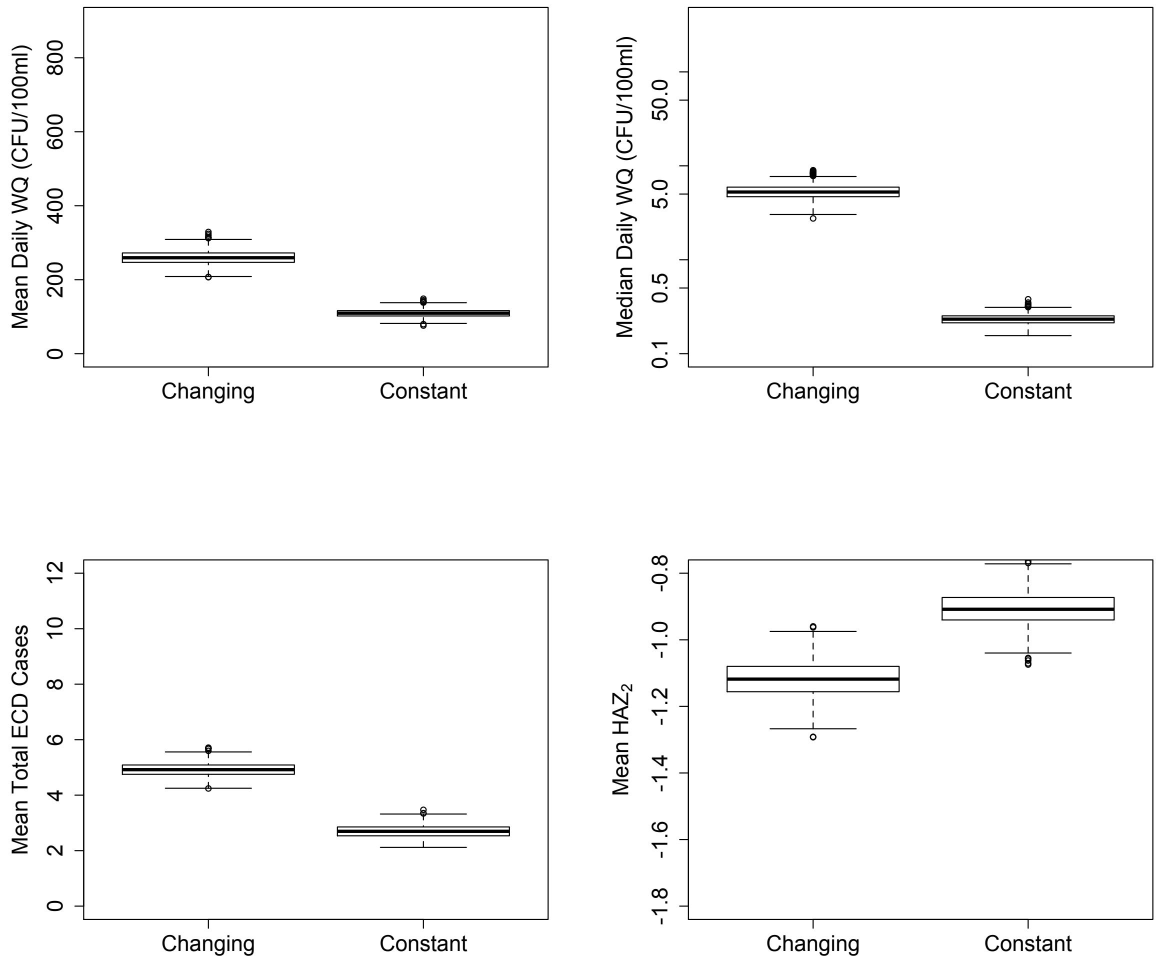

Figure 4.3: *Plots showing the mean and median daily water qualities, the mean total ECD cases and HAZ_2 to highlight the effects of changing filter effectiveness. The changes (which are generally declines) do have significant effect on all four metrics compared to simulations run when the microbial effectiveness was held constant. These results highlight the need for improved container cleaning.*

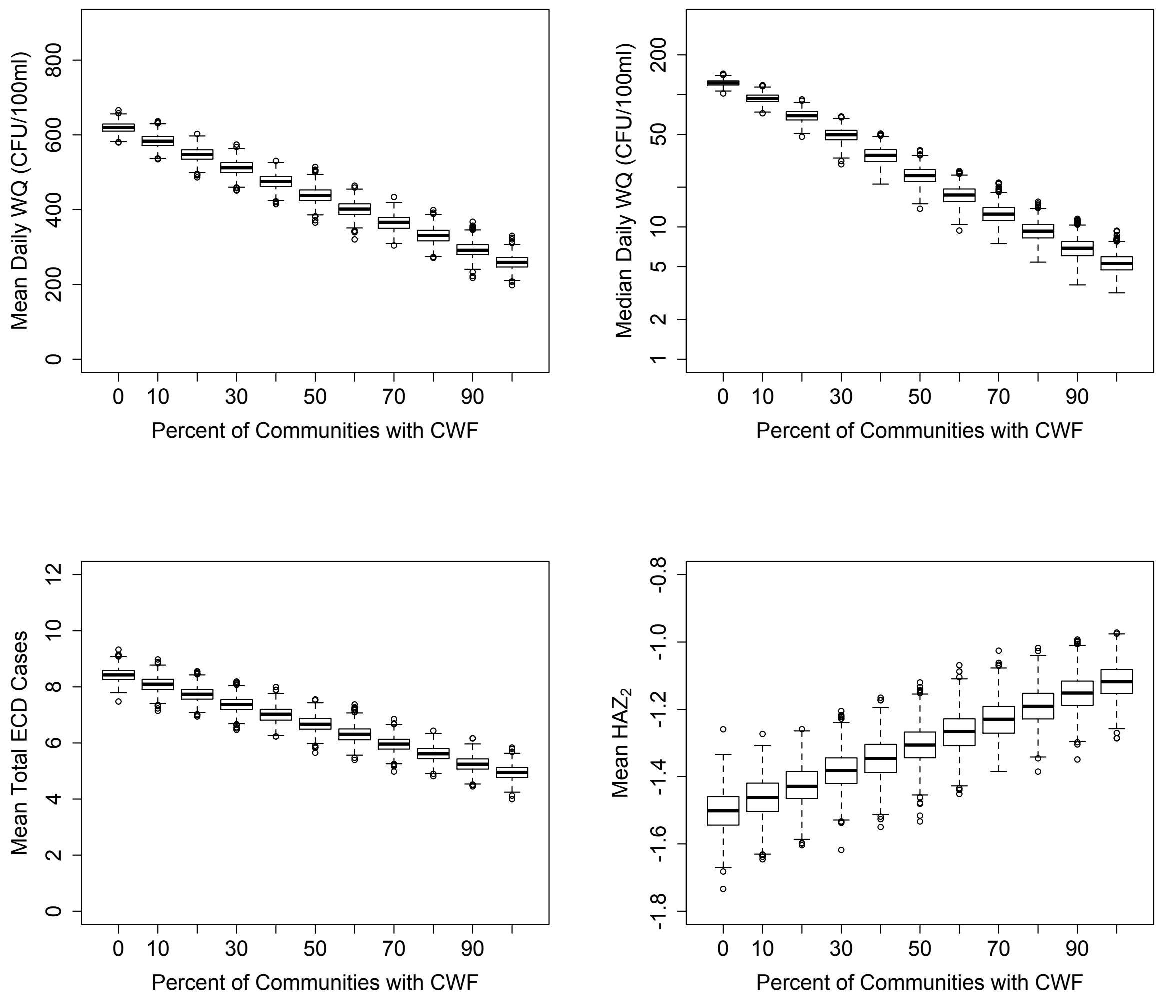

Figure 4.4: *Plots showing the mean and median daily water qualities, the mean total ECD cases and HAZ_2 as a function of intervention size. Results indicate linear improvements with increasing percentages in all metrics except for median daily water quality which shows a log-linear relationship.*

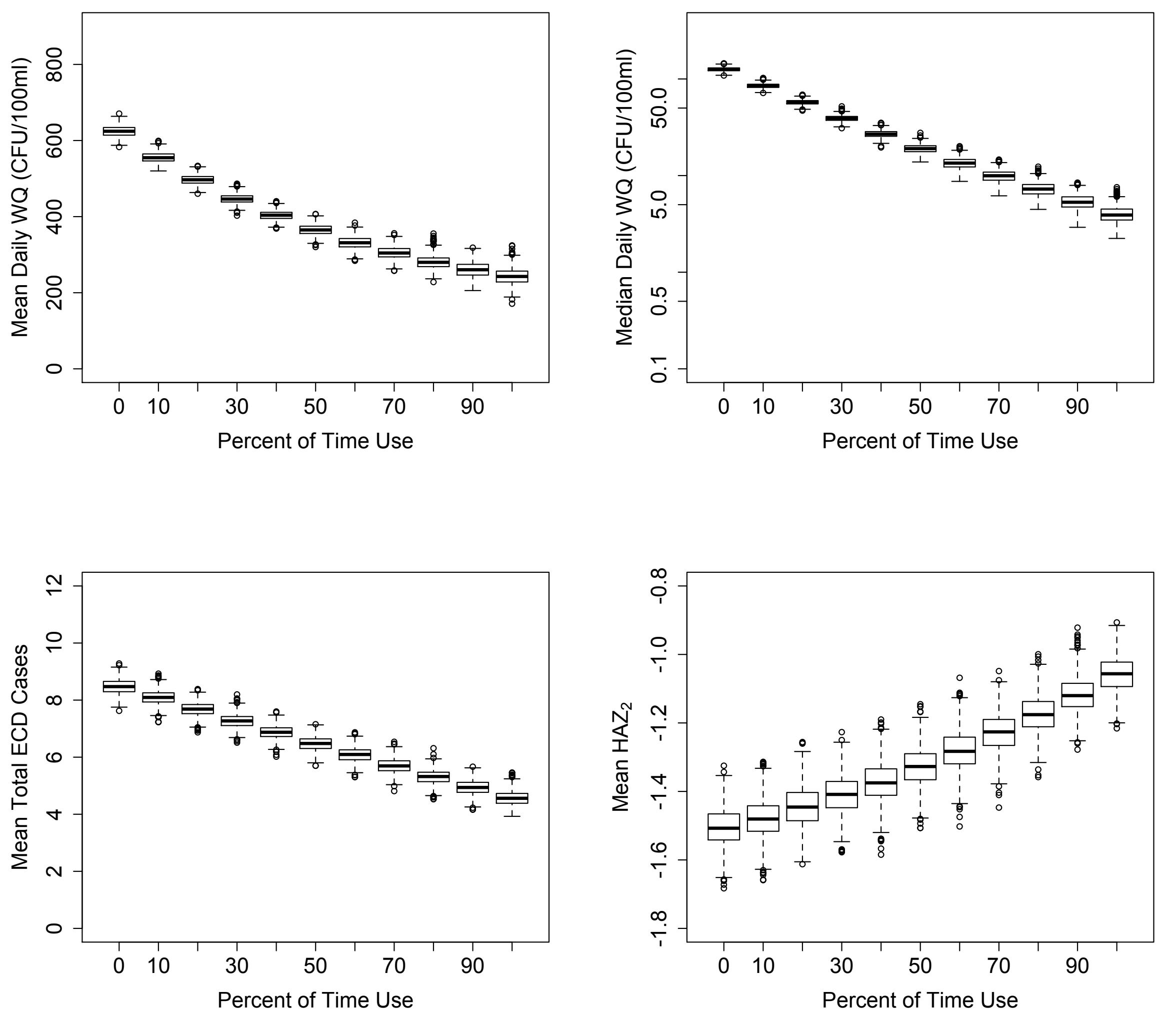

Figure 4.5: *Plots showing the mean and median daily water qualities, the mean total ECD cases and HAZ_2 as a function of usage. Results indicate linear improvements with increasing usage in all metrics except for median daily water quality which shows some log-linear behavior. Results highlight the need for consistent use to maximize benefits.*

outcome variables, while the outcome variables changed quickly for inferior removal efficiencies. This suggests that 3 log removal efficiencies are sufficient to reduce ECD cases.

As a further test of the realistic effects of the microbial effectiveness changes that occur over time, the model was run for the median microbial log removal effectiveness at the 0, 1 and 3 year points which were 2.92, 1.63 and 0.42 respectively for the South Africa data as highlighted in Section 4.2.2. These results are shown in Figure 4.7. Those results indicate that mean water quality, median water quality, mean ECD cases and HAZ_2 all changed significantly ($F = 222366$, $p < 0.001$; $F = 662298$, $p < 0.001$; $F = 16083$, $p < 0.001$; and $F = 8130.8$ $p < 0.001$ respectively). Furthermore mean water quality went from 72.0 to 268.5 CFU/100 mL and median water quality went from 0.1 to 32.6 CFU/100 mL, mean ECD cases increased from 1.39 to 7.48, and HAZ_2 from -0.68 to -1.39.

More frequent cleaning had a positive effect on the outcome variables as can be seen in Figure 4.8. There were significant variations between the outcome metrics of mean water quality ($F = 43127$, $p < 0.001$), median water quality ($F = 32609$, $p < 0.001$) and ECD cases ($F = 90135$, $p < 0.001$). Daily cleaning improved mean water quality compared to not cleaning by 108.9 vs 253.1 CFU/100mL, median daily water quality 0.24 vs 5.31 CFU/100mL and ECD cases by 2.70 vs 4.88. It is notable that less frequent (i.e. bi-monthly) cleaning was nearly as effective as daily cleaning.

Linear decreases in usage led to highly significant variations in the outcome metrics of mean water quality ($F = 53870$, $p < 0.001$), median water quality ($F = 40595$, $p < 0.001$), ECD cases ($F = 128647$, $p < 0.001$) and HAZ_2 ($F = 32897$, $p < 0.001$). Even realistic usage declines of 20% per year resulted in a deterioration of the out-

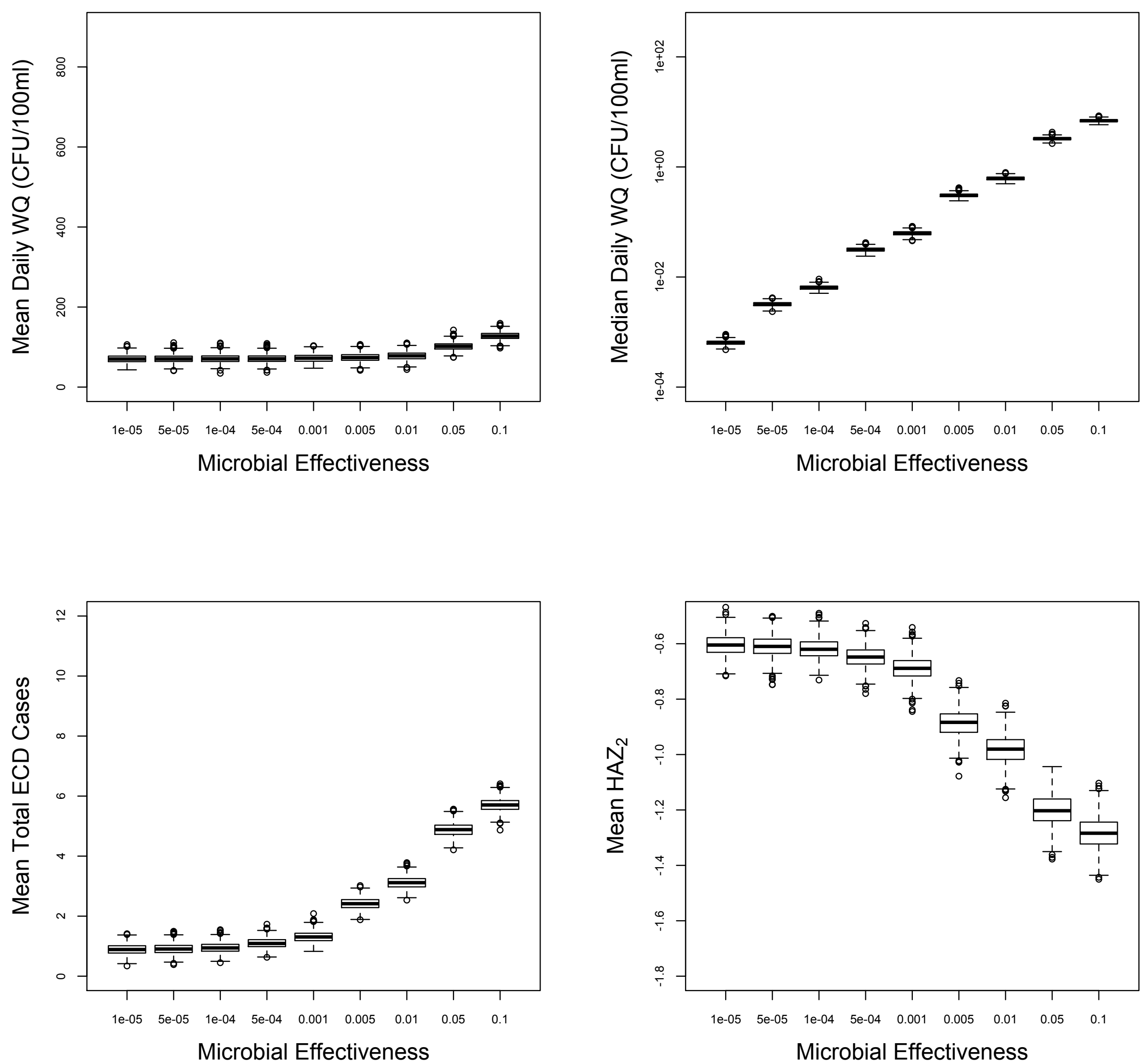

Figure 4.6: *Plots showing the mean and median daily water qualities, the mean total ECD cases and HAZ_2 as a function of microbial effectiveness. Plots indicate that outcome variables are not strongly correlated with microbial effectiveness when log reduction values are better than 0.001 (LOG 3). This fact has important implications when designing point-of-use water treatment devices.*

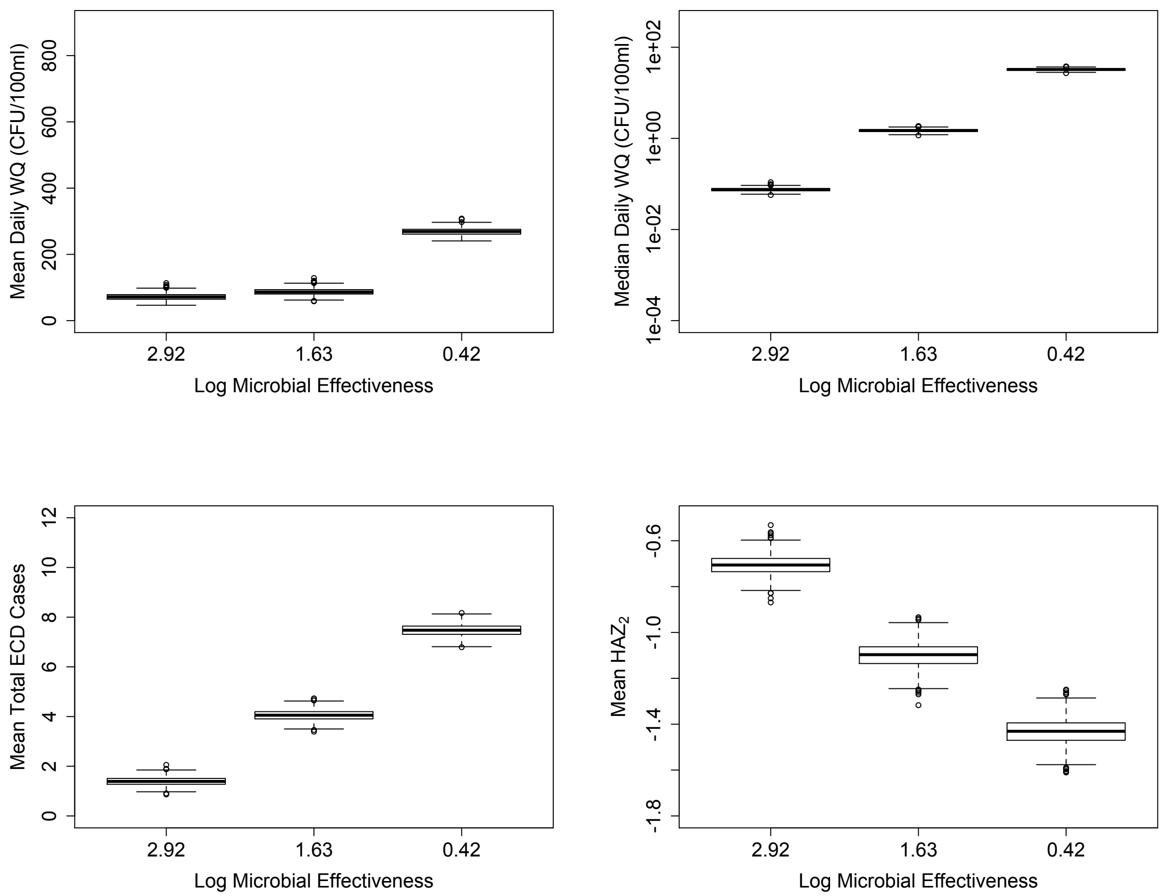

Figure 4.7: *Mean and median daily water quality, mean ECD cases and HAZ_2 data for median log removal efficiencies at the 0, 1 and 3 year mark of the South African data. Evidentially the declining effectiveness has a profound effect on the outcome metrics.*

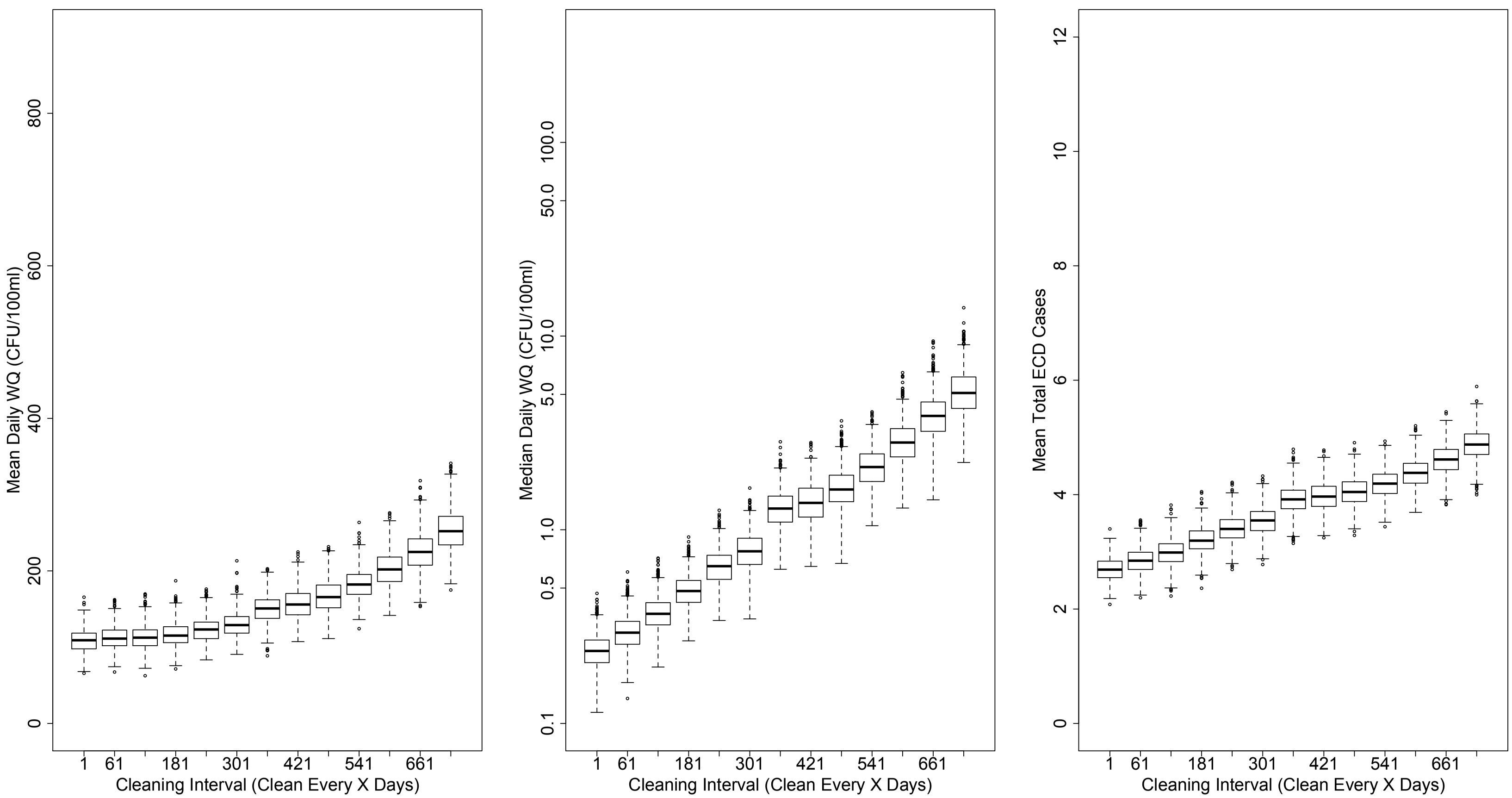

Figure 4.8: *Plots showing the mean and median daily water qualities and the mean total ECD cases a function of cleaning interval. Daily cleaning significantly improved outcome variables compared to less frequent cleaning. However, even bi-monthly or cleaning every six months was highly beneficial.*

come variables. A 20% vs 0% decline changed the outcome variables as follows: mean water quality 287.1 to 259.9 CFU/100mL; median water quality from 11.89 to 5.60 CFU/100mL; ECD cases from 5.48 to 4.93; and HAZ_2 increases from -1.12 to -1.19.

Figure 4.10 shows how the outcome variables of median daily water quality and ECD cases vary as a function of breakage date and the percent of CWFs that break on that day. The outcome variables are more sensitive to breakage date for the higher breakage percentages. In general, the longer filters are in use, the more effective they will be in preventing ECD, but the rate of decrease changes markedly at the one year mark.

The graphs in Figure 4.11 summarize a behavior space analysis of threshold water quality and baseline percent use. In general the outcome metrics are highly sensitive to the threshold water quality (the water quality above which a household is about twice as likely to use the CWF) for values above 10 CFU/100mL. The baseline usages of 40-60% showed the highest sensitivity to threshold water quality although even the more realistic usages percentages (i.e. 90%) showed a marked improvement. Evidentially, the propensity of households to use CWFs more frequently when water is of poor quality has a protective effect on outcome variables.

An investigation of the outcome metrics as a function of filter price is shown in Figure 4.12. It is clear from these diagrams that large improvements in water quality, ECD cases and child growth stunting could be realized through the ability of households to have filters available for purchase for a reasonable price. This is particularly true with high breakage rates. Interestingly high breakage rates led to very good outcome metrics for low filter prices because microbial effectiveness generally declines with

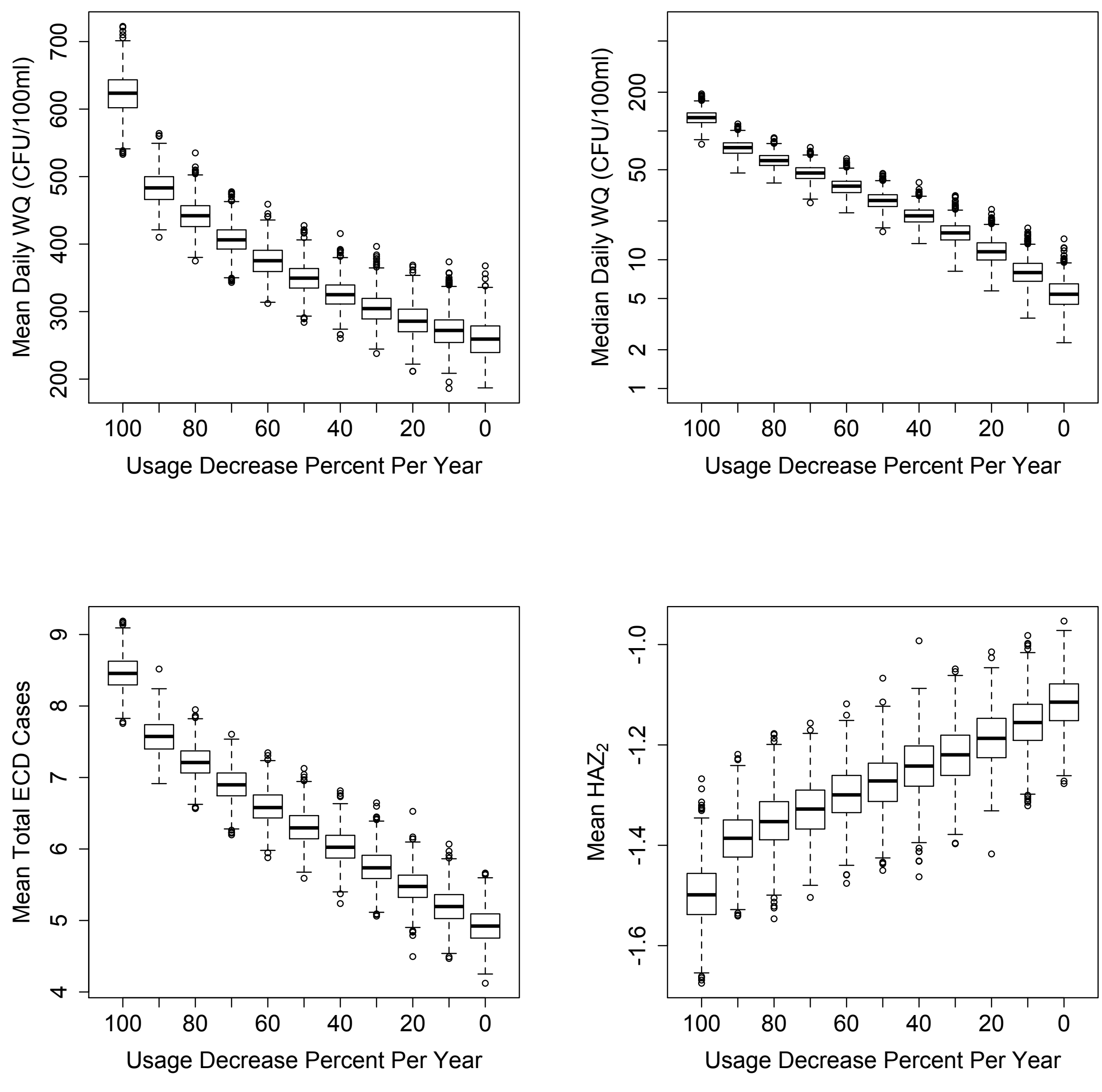

Figure 4.9: *Plots showing the mean and median daily water qualities, the mean total ECD cases and HAZ_2 as a function of linear decreases in usage. Even small usage decreases would have large effects in interventions lasting more than two years.*

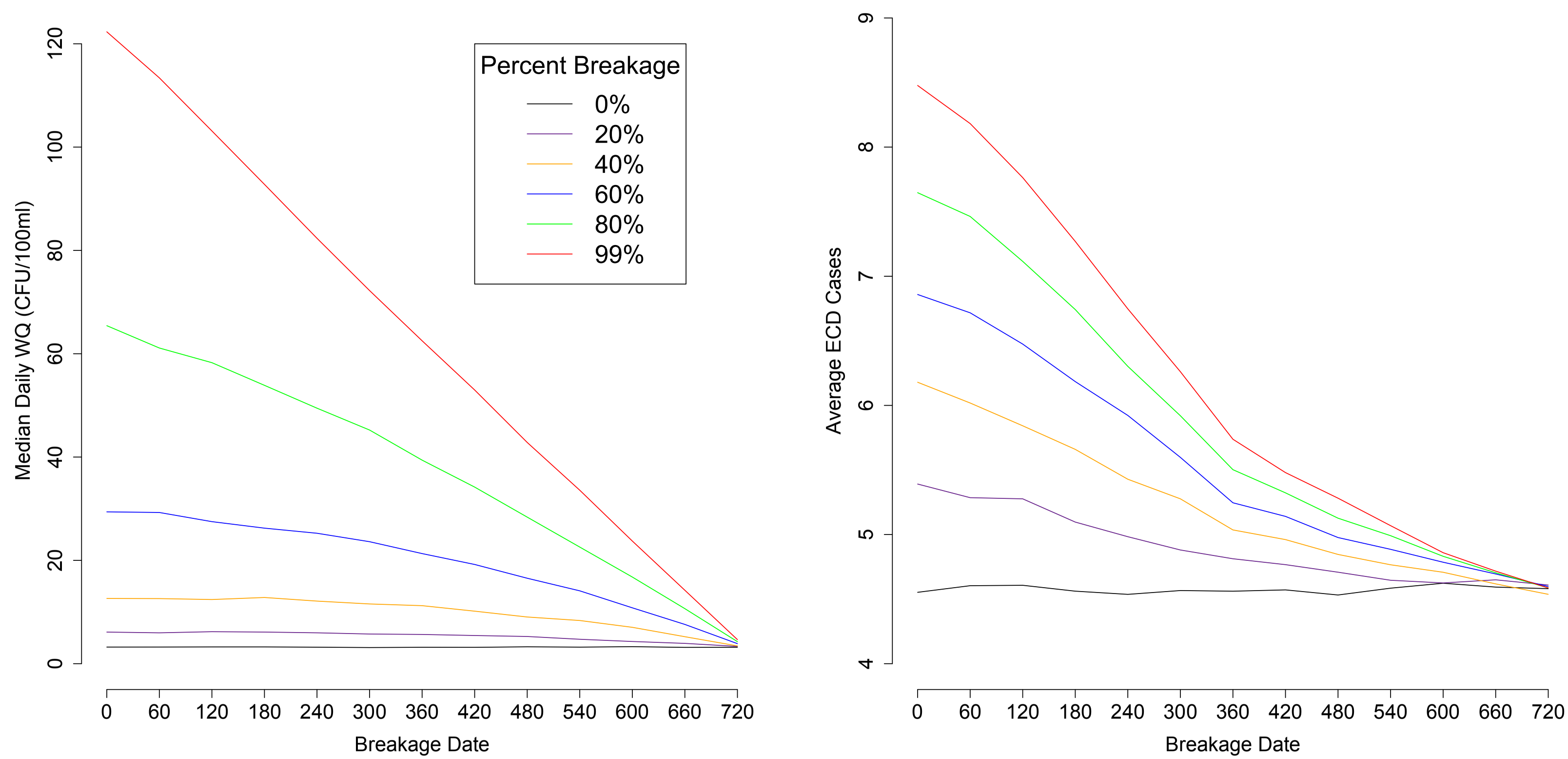

Figure 4.10: *An analysis of how breakage date and percent breakage affect the outcome variables of median daily water quality and average ECD cases. In both cases, the outcome variables were more sensitive to breakage date for high breakage percents.*

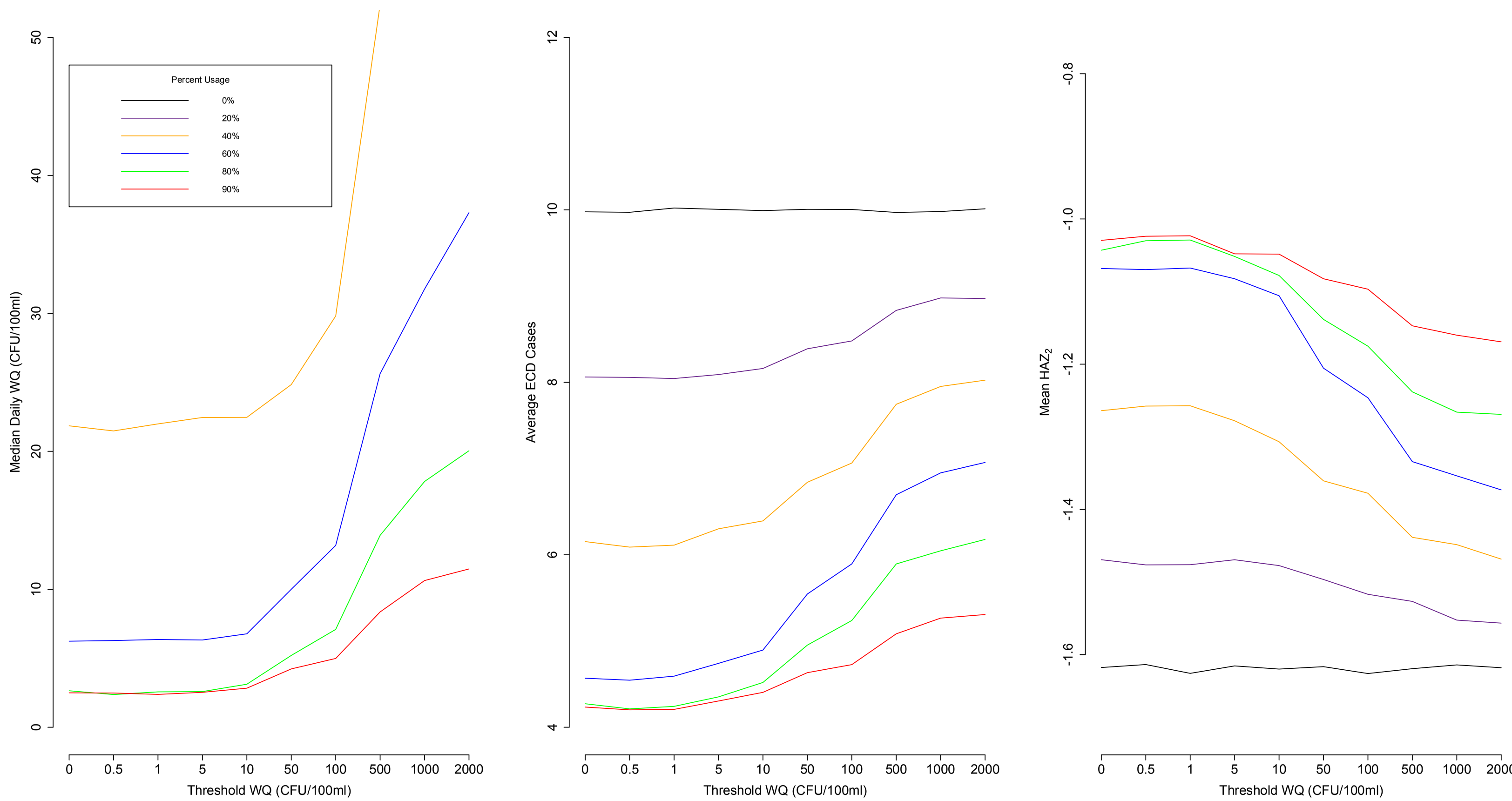

Figure 4.11: *Households' propensity to treat their water when it is of a given water quality or worse is shown for the outcome variables of median daily water quality, average number of ECD cases and mean HAZ_2. The three metrics show high sensitivity to this threshold water quality above 10 CFU/100mL. The metrics are most sensitive to the threshold when usage is 40-60%.*

time and newly purchased filters would have better microbial removal efficiencies than the older ones they replace. For realistic breakage rates of around 20% for the two year period there was a deterioration of median water quality from 2.57 to 5.31 CFU/100mL and ECD cases from 4.41 to 4.91 between the lowest and highest filter prices.

4.3.3 Multi-Parameter Behavior Space Analyses

Two separate multi-parameter behavior space analyses were conducted to further elucidate system complexities and identify the parameters most responsible for large improvements in outcome variables.

The variable combinations of the first analysis are given in Table 4.3. A cumulative distribution function (CDF) of the ECD rates resulting from that analysis is given in Figure 4.13. That figure indicates that the majority of parameter combinations result in 8-9 ECD cases during the first two years of life. However, a minority of optimized parameter combinations can lead to vast reductions in ECD cases.

Figure 4.14 is comprised of normalized histograms of the six parameters varied as part of the first multi-parameter analysis. Each histogram is divided into ECD rates of 1-9+ for each parameter value modeled. Very low ECD rates (< 2 ECD cases) could be achieved only with high levels of usage and prevalence, low levels of usage decrease, and moderate to high levels of microbial effectiveness. Breakage date and breakage percent were less important parameters. These low levels of ECD could be realized for microbial effectiveness levels of up to 10^{-3} and any breakage date and breakage percent. Conversely high rates of ECD were seen when usage and prevalence were low and usage decreases were large. This was true irrespective of breakage date,

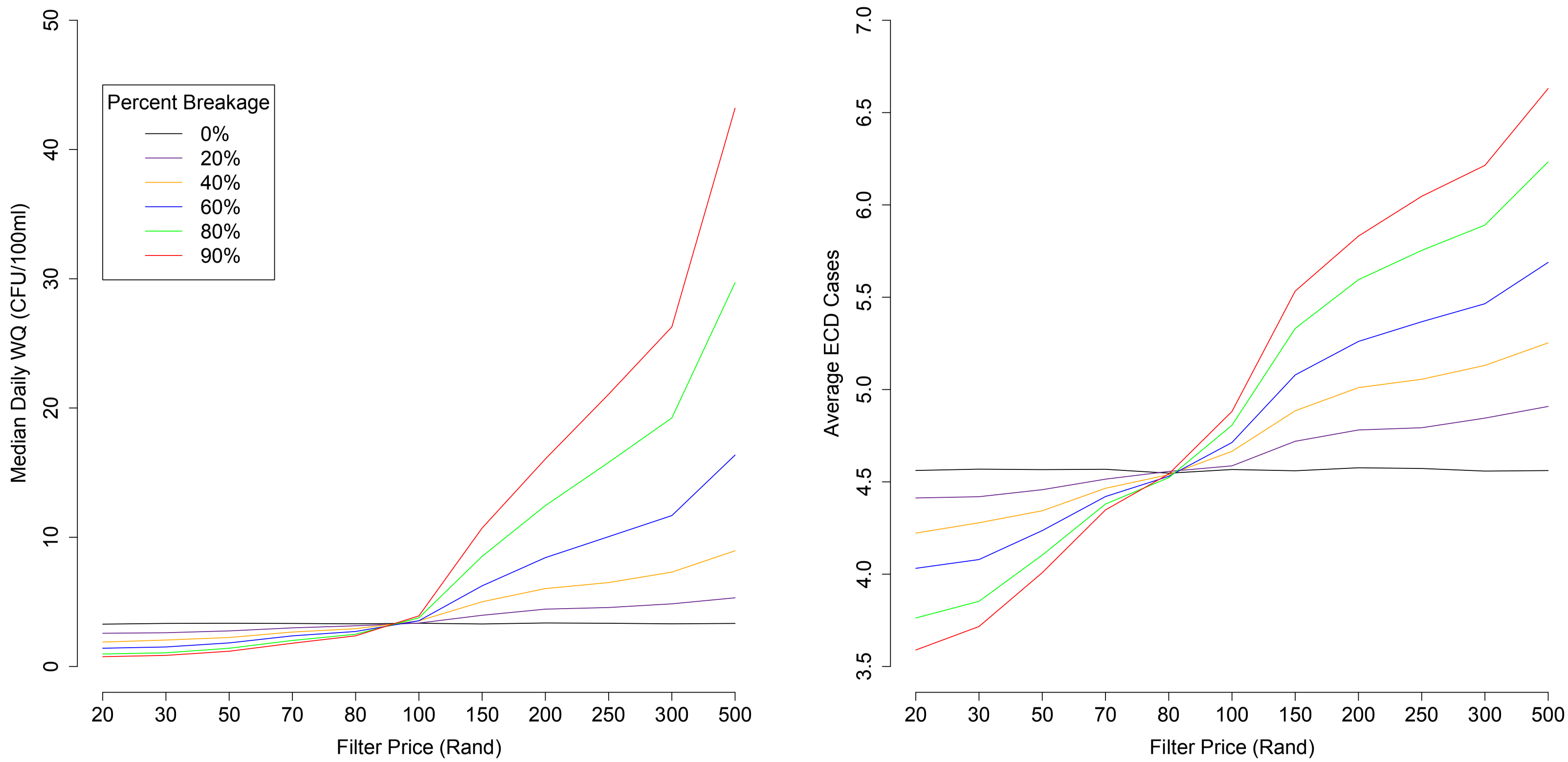

Figure 4.12: *Median water quality, average ECD cases and mean HAZ_2 as a function of filter price in South African Rand. Interestingly, higher breakage percentages had improved outcome metrics for low filter prices since the microbial effectiveness of new filters is generally superior to older filters. All three outcome variables showed significant improvement at around 100 Rand, which was the median WTP.*

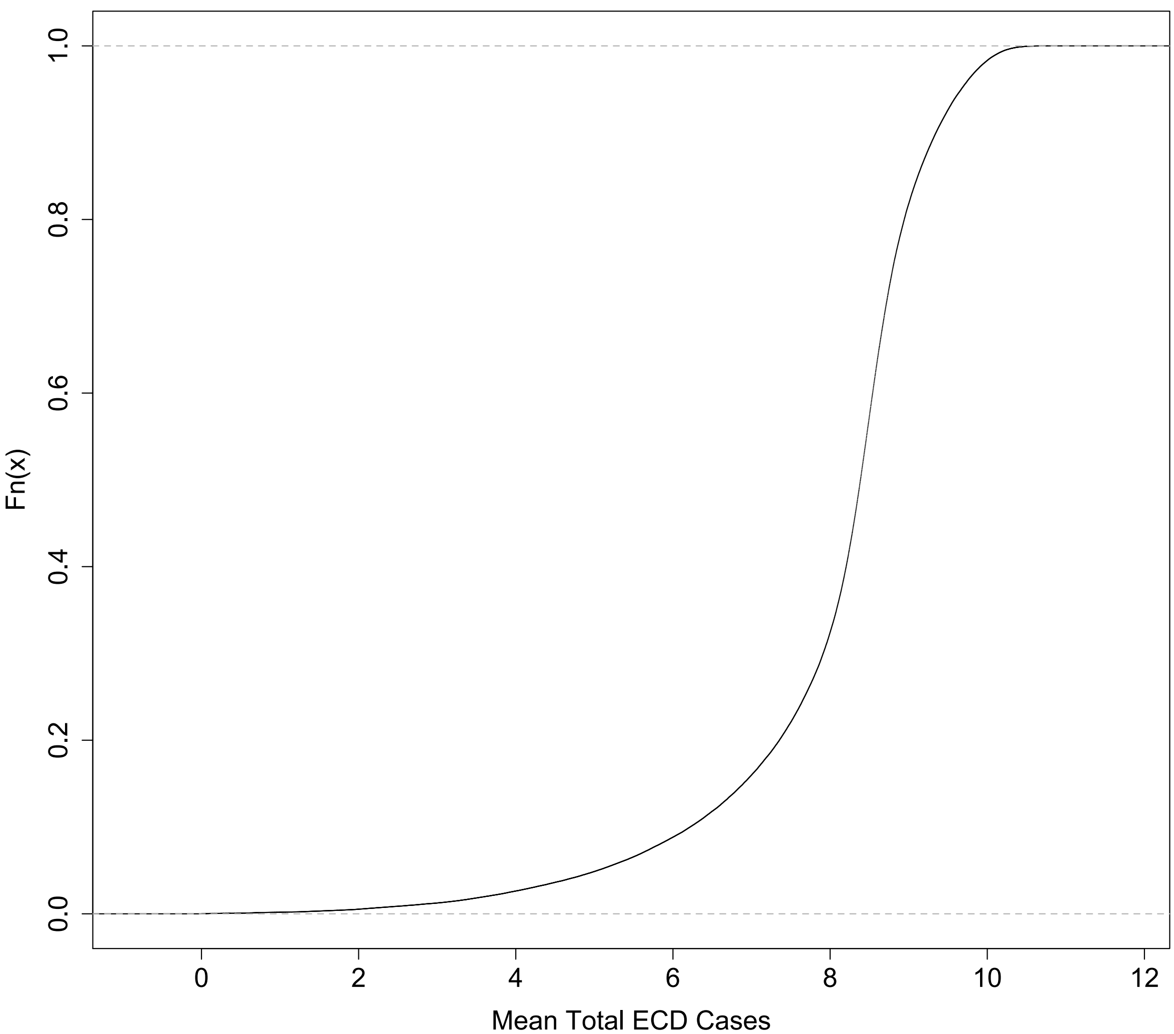

Figure 4.13: *Cumulative distribution function of multi-parameter behavior space analysis. Figure indicates that the vast majority of parameter combinations lead to ECD rates of 8 to 9 over two years. However, a minority of parameter combinations result in very low or very high ECD incidences.*

microbial effectiveness or breakage percent.

A second behavior space analysis was conducted to explore several of the other parameters. The cumulative distribution function for this analysis is shown in Figure 4.15. That figure indicates that most parameter combinations result in ECD rates of 6-8 with a minority resulting in lower and higher rates.

As with the first analysis, filter usage, prevalence and usage decrease were all the most important variables that had to be optimized to reduce ECD incidence. In addition, Figure 4.16 indicates that frequent (i.e. daily or monthly) CWF cleaning and low water treatment thresholds were also important (although not necessary) factors in achieving very low ECD rates. As with the previous analysis, ECD rates could be very low irrespective of breakage percents and/or dates. The availability of new filters to be purchased had little effect on ECD rates compared to the other metrics even when prices were very low.

4.4 Discussion

By taking a systems approach to model a ceramic filter intervention in a developing world location, we have attempted to uncover the complex coupled human/engineered/natural system dynamics that are critical for understanding the long-term sustainability of a ceramic water filter intervention. Specifically, we have modeled how important declines in microbial effectiveness due to improper maintenance can be over the long term. In fact, we have shown that, on average, filters might be nearly useless after 2-3 years of use due to declining microbial effectiveness, a problem that might be largely rectified with improved cleaning frequency. We have also shown the critical importance of compliance. In addition, we have predicted

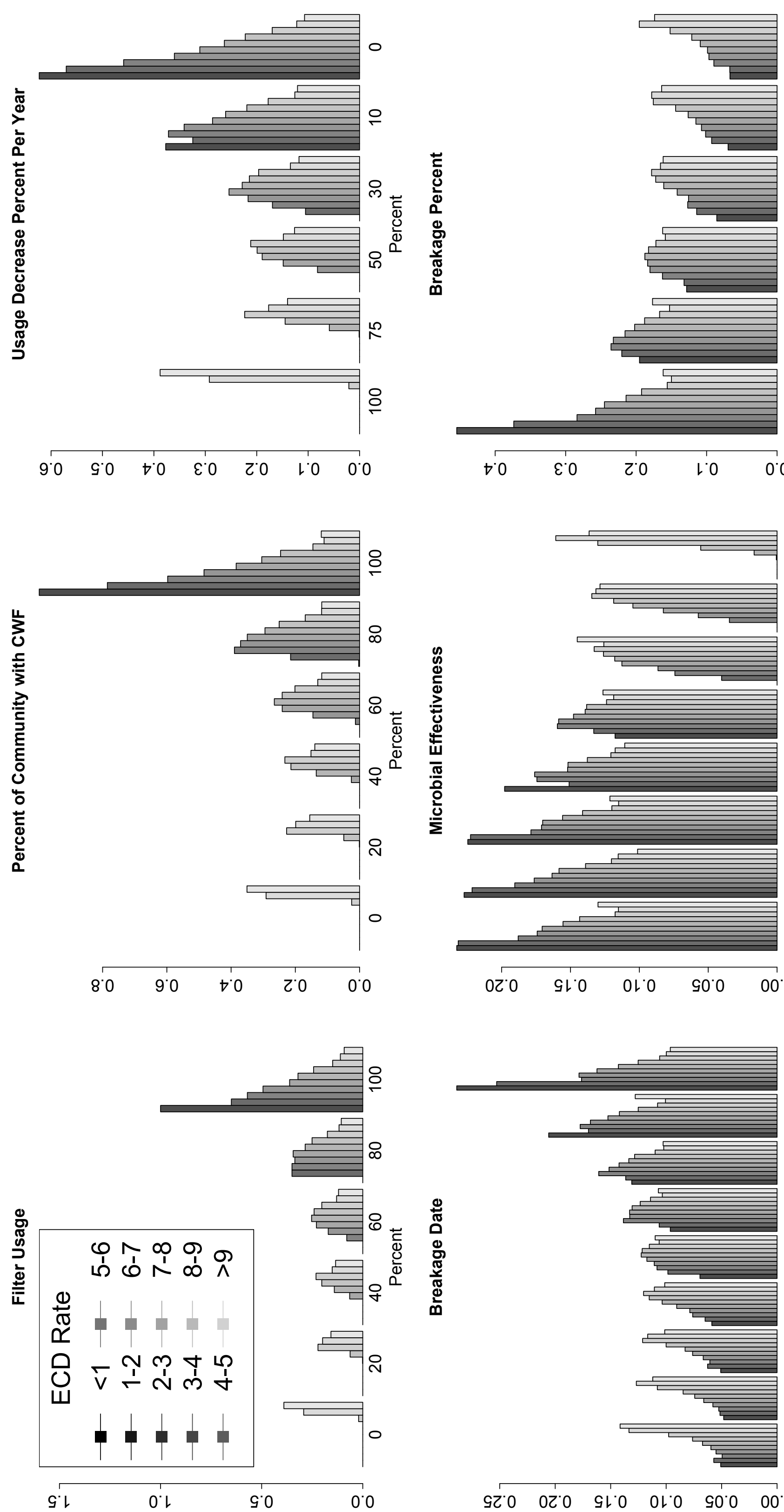

Figure 4.14: *Normalized histograms of the six different parameters varied in the first multi-parameter behavior space analysis. Results are divided into ECD rates ranging from 1-9+ over the parameter values modeled. Filter usage, prevalence and yearly usage decrease were all important parameters while breakage date and breakage percent were less important. Microbial effectiveness generally needed to be 10^{-3} to achieve optimal results, and better removal efficiencies were not necessarily critical.*

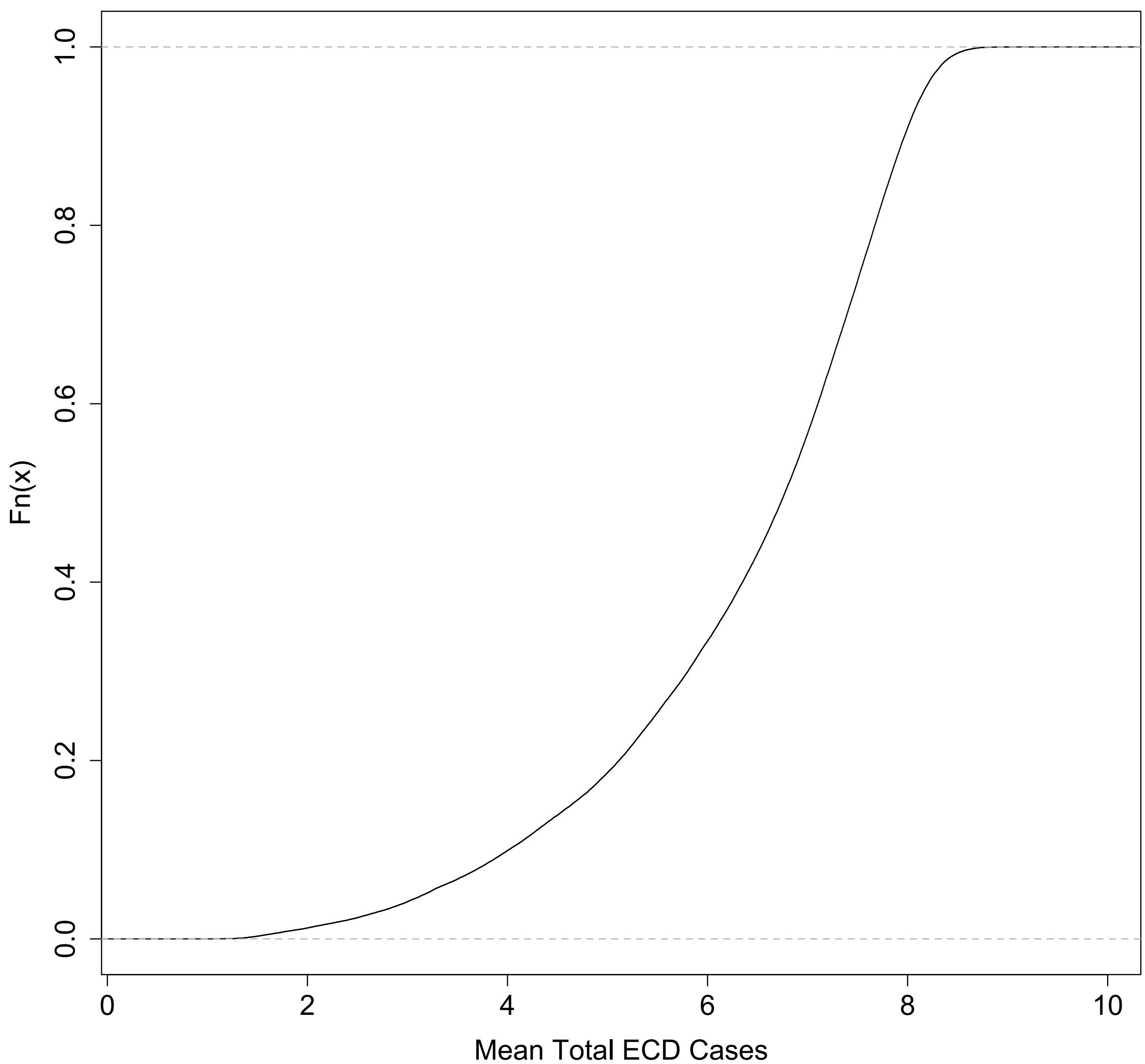

Figure 4.15: *A cumulative distribution function for the second multi-parameter analysis conducted. It is evident from this figure that the majority of variable combinations lead to ECD rates of 6-8 with a minority of combinations results in significantly lower ECD rates.*

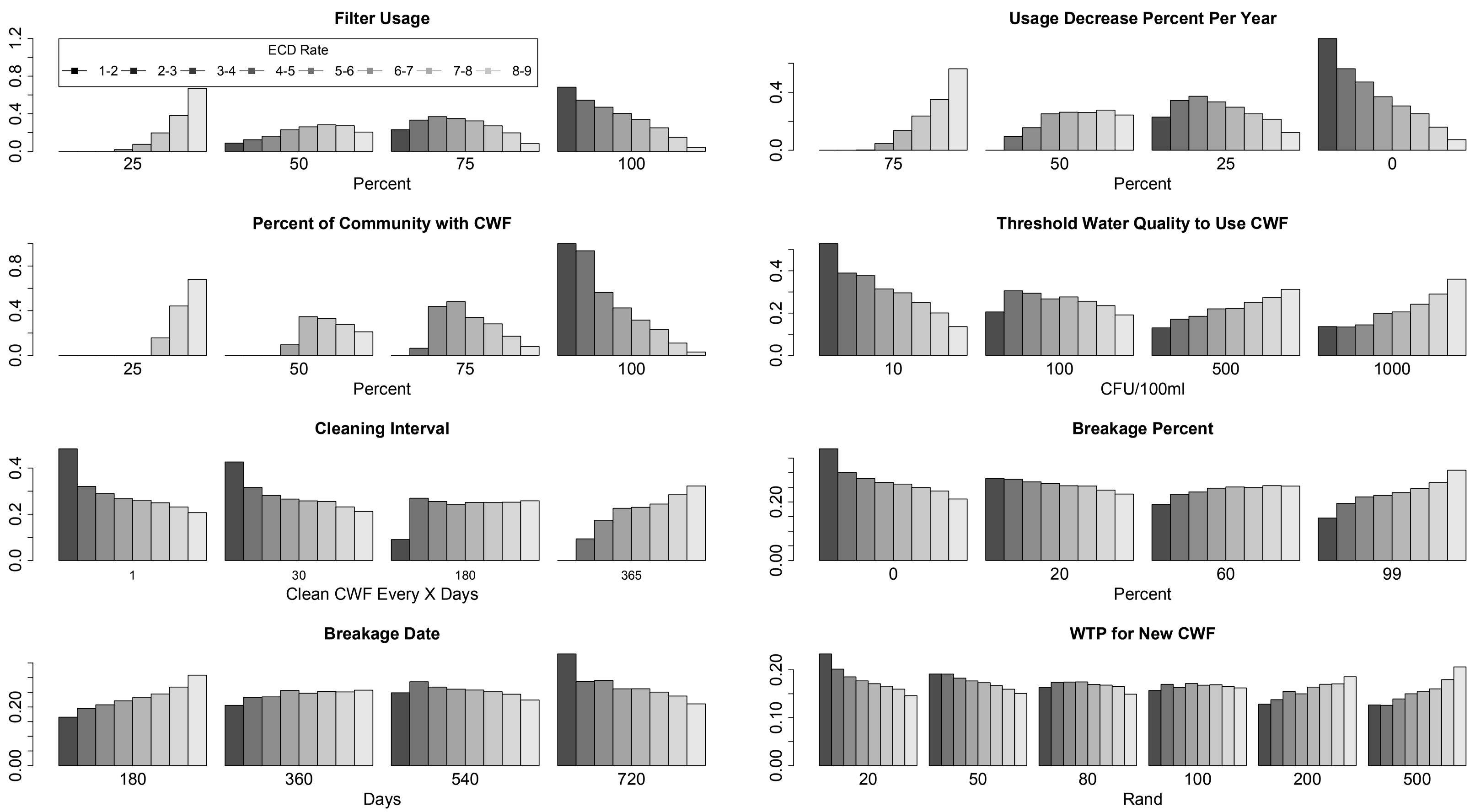

Figure 4.16: *Normalized histograms of eight different parameters investigated in the second parameter space analysis. Results given for 2-8+ ECD incidences over the two year period. The darker shades represent lower ECD incidences. In addition the usage, prevalence and usage decreases seen in the previous analysis, cleaning interval and threshold water quality were also parameters that could influence ECD rates. WTP for new filters was not as important of a parameter.*

that microbial effectiveness levels less than 3 log removal do not result in optimal outcomes. Finally, we looked at several other aspects including a household's propensity to use their filter more often when water quality was poor, filter breakage and the availability of new filters for purchase as other potentially important confounding factors.

The most important conclusion of this work is that behavioral factors can have a huge impact on the long-term sustainability of a CWF intervention. The presumed contamination of the lower reservoir that leads to the gradual decline in CWF effectiveness plays a significantly detrimental role in the ability of these filters to reduce ECD in young children. We showed that periodic cleaning can have a significantly positive effect on the outcome variables. Even cleaning the lower reservoir every six months can help. Furthermore, by taking the median log reduction values for the 0, 1 and 3 year measurements, we have shown that ECD rates after 3 years might be, on average, above 7 which indicates that the filters are nearly useless after that time period.

A complementary factor is the fact that inconsistent use of the filters can have a large impact on the outcome metrics. This is especially important given that upwards of 95% of children under five reported drinking untreated water the previous day during a recent household water treatment trial (Boisson *et al.* , 2010). Another interesting result from our work was the investigation into uniform linear decreases in usage. We showed that the linear decreases of 2% per month reported previously (Brown *et al.* , 2009) can have a negative effect on outcome variables, while larger linear decreases led to far worse outcomes. This finding reinforces the need for implementing agencies to consider long term sustainability.

The analysis of breakage precent and breakage date illustrated how detrimental these two factors can be on the sustainability of a CWF campaign. The realistic breakage percentage of around 80% over the two year period show how harmful breakage can be especially when the filters break early in a child's life. Complementing this experiment is our study of how the availability of a CWFs for purchase can help mitigate high breakage rates. In our model, median water quality was not highly dependent on filter price below 100 Rand, but it deteriorated quickly above that amount. Based on this result, implementing agencies should strive to keep prices below this value which is equivalent to $11.23 USD.

The threshold experiment which looked at how households who treated their drinking water when it was above a given threshold also have important implications for policy makers and community health workers. According to our results, CWF users can get away without using their filters if water quality is good, but the more adept they are at recognizing poor quality water, and using their filters during high risk consumption, the more benefit they will receive. It is especially important for users to recognize when their water quality contains 10 CFU/100mL of coliform bacteria or more. Although there is no definitive way for community members to know their water quality, this finding encourages implementing agencies to educate communities about the hazards of drinking from acutely contaminated water sources and to treat their water if they must collect from those sources.

The multi-parameter investigation provided us with valuable information about which parameters are most important and therefore most critical when trying to reduce ECD. The first notable fact about Figures 4.13 and 4.15 is that the majority of parameter combinations led to ECD rates centered around 6 to 9 for the first two years of a child's life. However, in both cases, a notable minority of parameter combinations led to very good outcomes. In the case of the first multiple parameter behavior space analysis in Figure 3.6 it is clear that filter usage, prevalence and linear declines were all the most important parameters. Optimal results could be achieved with any breakage date or percent as long as microbial effectiveness was greater than 10^{-3}. The second multiple parameter behavior space analysis added several other interventions. The major conclusions about filter usage, prevalence and linear declines held as before. However, cleaning interval and threshold water quality were also important parameters. Although houses could achieve good outcomes without frequent cleaning or recognition of poor water quality, these two behaviors were positively correlated with the better outcomes. As was found earlier, breakage percent, date and the availability of new filters if a household was WTP for a new filter were not strongly correlated to outcome metrics.

Our model predicted that the benefits of improved microbial efficiency were less apparent for log reduction values of 3 or greater. This result was also found by Enger *et al.* (2012a) for 95% compliance levels. The fact has important implications for the fabrication of filters. In-country tests of filters have shown them to be 92 - 99% effective (Kallman *et al.* , 2011; Brown & Sobsey, 2010) at removing *E. coli* bacteria which should be improved to achieve optimal results.

Our basic model predicts that ECD can be reduced by approximately 41.3% with the introduction of a ceramic filter campaign assuming a 90% usage rate. This result is highly consistent with the 46% found by Brown *et al.* (2007). Other studies that investigated the use of ceramic filter candles in a similar arrangement found relative risks of 0.30 (95% CI 0.19 - 0.47) (Clasen *et al.* , 2004), 0.40 (95% CI 0.25 - 0.64) (Clasen *et al.* , 2005) and 0.47 (95% CI 0.24 - 0.92) for the general population (Clasen *et al.* , 2006). A final study found an odds ratio of 0.17 (95% CI 0.080.37) (Du Preez *et al.* , 2008) for children 24-36 months of age. However all of these studies had large uncertainty and none of these studies were blinded and are therefore subject to recall bias. A meta-analysis of these studies indicates a combined relative risk of 0.34 (95% CI 0.26 - 0.43) (Hunter, 2009). This combined relative risk is less than the 0.59 calculated for this study. However, Wood *et al.* (2008) suggest a ratio of odds ratios of 0.75 (0.61 - 0.81) to account for the lack of blinding. This 25% correction would decrease our relative risk to 0.44, which is highly consistent with most studies cited above.

Our study can also be compared to the Hunter (2009) study which investigated the longitudinal effectiveness of a ceramic filter intervention. Their study estimated a relative risk of 0.37 (95% CI 0.19 - 0.71) after 52 weeks of follow-up. This value is statistically equivalent to the 0.64 found by our ABM using the day 365 microbial effectiveness values. Correcting our value by 25% would result in a 0.48 relative risk, which is even closer to their reported value.

Although our ABM is well tested (Mellor *et al.* , 2012a), is consistent with previously reported results and produces logical conclusions, there are a few notable limitations. First, our study was designed to investigate household water quality generally and the ECD incidences and growth stunting of children under two years of age. Children of this age range are highly sensitive to poor water quality and are likely to experience growth stunting as a result of it (Checkley *et al.* , 2008). However, since we only ran our model for two years, it is difficult to make predictions about the sustainability of a CWF campaign longer than this timeframe. It is likely that filters become so contaminated as to become nearly useless after this time, and that later breakage dates are more important for children born some time after a household receives a filter.

Our approach could also benefit from additional field research about exactly how frequently residents use their filter. It also would be useful to have additional field research into exactly why the filter effectiveness declines with time and ways to clean the filters. Such evidence would inform stakeholder efforts to improve interventions.

Our conclusions lead us to better understand both the results of previous randomized field trials as well as inform the development of future trials. Based on these results, the large heterogeneity seen in previous trials of ceramic water filters and other point-of-use interventions could be due to variations in usage, cleaning regimes, usage declines or a household's propensity to treat water when it is of particularly poor quality. It is therefore imperative that future trials accurately measure exactly how often households use their filters, how frequently participants drink from non-treated water even when "using" the filters and how compliance might decline over time or vary between household members. Researchers must also have an understanding of each household's propensity to clean their filter and the confounding effects that might have. Future studies should also include all potential co-variates which might have a impact on outcomes. For instance, it is possible that the filters might reduce ECD incidence by a greater amount in crowded households or in households with low levels of eduction who might be less likely to maintain their filters or who might reserve the purified water only for certain household members. Lastly, these results re-enforce the need for researchers to conduct trials of 2-3 years or more in order to understand the long-term effectiveness of the filters at improving water quality and reducing ECD cases. Shorter trials simply fail to capture the CWFs true effectiveness. Understanding these covariates will likely lower literature values for CWF effectiveness.

4.5 Conclusion

We have illustrated a novel complex systems technique for understanding the sustainability of a ceramic water filter intervention at improving household drinking water quality, reducing ECD incidences and improving child growth in a resource-limited setting. Our results indicate that human behaviors are a primary driver of our outcome metrics and that a ceramic filter intervention has the ability to reduce ECD incidences by 41.3%. We found that filter microbial effectiveness declines so much after 3 years that the average filter is nearly useless at preventing ECD. Baseline CWF usage, prevalence and linear usage declines all proved to be the most significant factors in the ability of such an intervention to improve our outcome variables. We also showed that log reduction values of less than 3 resulted in sub-optimal outcomes. In addition, we used our model to show how cleaning filters at least once every six months and low breakage rates might improve results. We also investigated how having filters available for purchase and having household recognize contaminated water sources might improve our outcome variables. A purchase price of 100 Rand or less in these communities could improve results and community recognition of water quality of 10 CFU/100mL or greater might likewise reduce ECD in communities. Overall, we suggest that a CWF intervention is an effective tool in the fight against ECD, but sustainability and community engagement should be the top priorities of implementing agencies.

CHAPTER 5

A Comparison of Three Point-of-Use Water Treatment Technologies

The following chapter is based on a study conducted by E. Kallman and V. Oyanedel-Craver in 2009-2010. This author was personally not involved in any of the study inception, design or field work components. However, this author did conduct the data analysis and interpretation presented in the following sections, will write the manuscript and will be a co-author on the resulting publication which will be submitted early this summer:

Kallman, E.N., Oyanedel-Craver, V.A., Mellor, J.E., Smith, J.A. (2013). "A Comparison of Three Point-of-Use Water Treatment Technologies", In Preparation.

5.1 Introduction

Worldwide, there are an estimated 1.1 billion people who lack access to improved water sources which is a primary cause of the 1.6 million children who die each year as a result of poor access to water, sanitation and hygiene (WASH) services

(WHO, 2006). Even when a community has a clean water source, water is frequently contaminated after collection, but before consumption (Wright *et al.* , 2004) which may be caused by a myriad of contamination sources as well as biological regrowth (Mellor *et al.* , 2012b). This is a particular problem for residents who must travel long distances to collect water (Mellor *et al.* , 2012c) and thus store their water for extended periods.

One technology that has consistently shown promise at improving household drinking water quality is a ceramic water filter (CWF). CWFs have been shown to be highly effective at removing bacteria in both laboratory (Brown & Sobsey, 2010) and field environments (Kallman *et al.* , 2011) and reducing ECD incidences in field trials (Fewtrell *et al.* , 2005). Although they have shown promise, some researchers have recently questioned their long-term sustainability (Hunter, 2009). One possible cause of this long-term decline in effectiveness is biological buildup that has been shown to be present in household water containers (Mellor *et al.* , 2013a) which are similar to the lower reservoir of CWFs. In fact, some have suggested that this presumed biological buildup coupled with poor cleaning regiments might be significant factors in their declining effectiveness (Mellor *et al.* , 2013b).

CWFs effectively remove bacteria both through size exclusion and the colloidal silver that is painted on or infused into the ceramic. The bactericidal properties of the applied silver is heavily dependent on the applied mass of colloidal silver (Oyanedel-Craver & Smith, 2008) while the bacterial growth inhibition by silver is dependent on the number of bacteria present (Sondi & Salopek-Sondi, 2004).

The bactericidal properties of colloidal silver led Potters for Peace to develop a novel ceramic torus painted with silver which can be placed in the bottom reservoir of a

CWF to inhibit bacteria growth. To test this technology we compared the microbial effectiveness of three technologies concurrently over the course of a year: a ceramic water filter (CWF); a CWF with the torus placed in the lower reservoir; and the chlorinated safe water system. The safe water system is supported and promoted by the US Center for Disease Controls and Prevention with the aim of training local distributors to produce and market hypochlorite as a disinfectant. Under this program, users apply a concentrated dose of free chlorine to a given volume of water stored in a clean and safe water storage container.

Therefore, the overarching goal of the study was to compare the longitudinal microbial effectiveness of the three technologies over a year-long period while testing the novel silver-impregnated torus's ability to slowly release silver thus improving the water quality in the lower reservoir.

5.2 Methods

5.2.1 Community Setting and Cohort

The study was undertaken in the community of San Mateo Ixtatán in the Guatemalan highlands. Access to suitable WASH infrastructure is severely limited and diarrhea is common in this resource-limited region making it the leading cause of death among children in Guatemala (Guatemala, 2002).

San Mateo Ixtatán is the poorest community in the poorest department of Huehuetenango and has a population of approximately 30,000 persons. Although the community has an extensive spring-fed water distribution system, the water is not treated and is of poor quality (Kallman *et al.* , 2011).

116 participants were recruited in June 2009 to participate in the study and were randomly assigned to one of three groups of approximately equal size as is shown in Figure 5.2. The first group received CWFs, the second group got CWFs with toruses placed in the bottom reservoir and the third group was given a safe water system bucket and could collect dosed chlorine bottles from a local distributor.

5.2.2 Torus Fabrication

The toruses were fabricated using a method similar to the method described by Kallman *et al.* (2011) to fabricate CWFs. In brief, approximately 60 lb of locally collected clay is combined with 8 to 10 lb of sieved sawdust. Once mixed, 10 L of water is added and the toruses are molded by hand. They are then allowed to air-dry for 8 days after which time they are fired at a temperature of 800^{o}C. The temperature was slowly increased from ambient by 75^{o}C/h for 4 h and then by 150^{o}C/h until the maximum temperature is reached. They are then hand painted with a 200 ppm silver nano-particle solution. The torus is shown in Figure 5.1.

5.2.3 Analytical Methods

Water samples were taken from both the untreated household taps and the effluent (treated) water from each POU treatment technology during each sampling period. Sampling took place in June 2009, January 2010 and June 2010 which will hereafter be referred to as Period 1, 2, and 3. The two samples taken from each household at each period were tested for total coliform bacteria during each of the three visits and *E. coli* bacteria during the last two visits using standard methods described in Section 2.2.4. Plates with too many colonies to count were recorded as having 2,000

Figure 5.1: *The torus being investigated in this study.*

CFU/100mL.

Silver concentration was measured each time using a Hach DR/4000 spectrophotometer and the Hach 8120 silver colorimetric method (Hach 2003). Chlorine levels were measured during the first two visits using Hach method 10069 which is equivalent to Standard Method 4500-C1-G for drinking water.

5.2.4 Statistical Methods

We calculated log reduction values from the influent and effluent water samples and analyzed them using IBS SPSS statistical analysis software version 21.0 (IBM SPSS Inc., Chicago, IL, 2011) as well as Microsoft Excel. We used repeated-measures Analysis of Variance (ANOVA) tests to see how silver concentrations and log reduction values varied between technologies and over time.

F-tests were used to assess variance for t-test analyses. Finally, standard one-way ANOVA analyses were also used. All tests were conducted using 95% confidence intervals.

All boxes in the box and whisker plots represent the median, upper, and lower quartiles. The whiskers represent the lowest and highest data still within a 1.5 x inter-quartile range from the median while the outlying circles represent data outside that 1.5 x inter-quartile range.

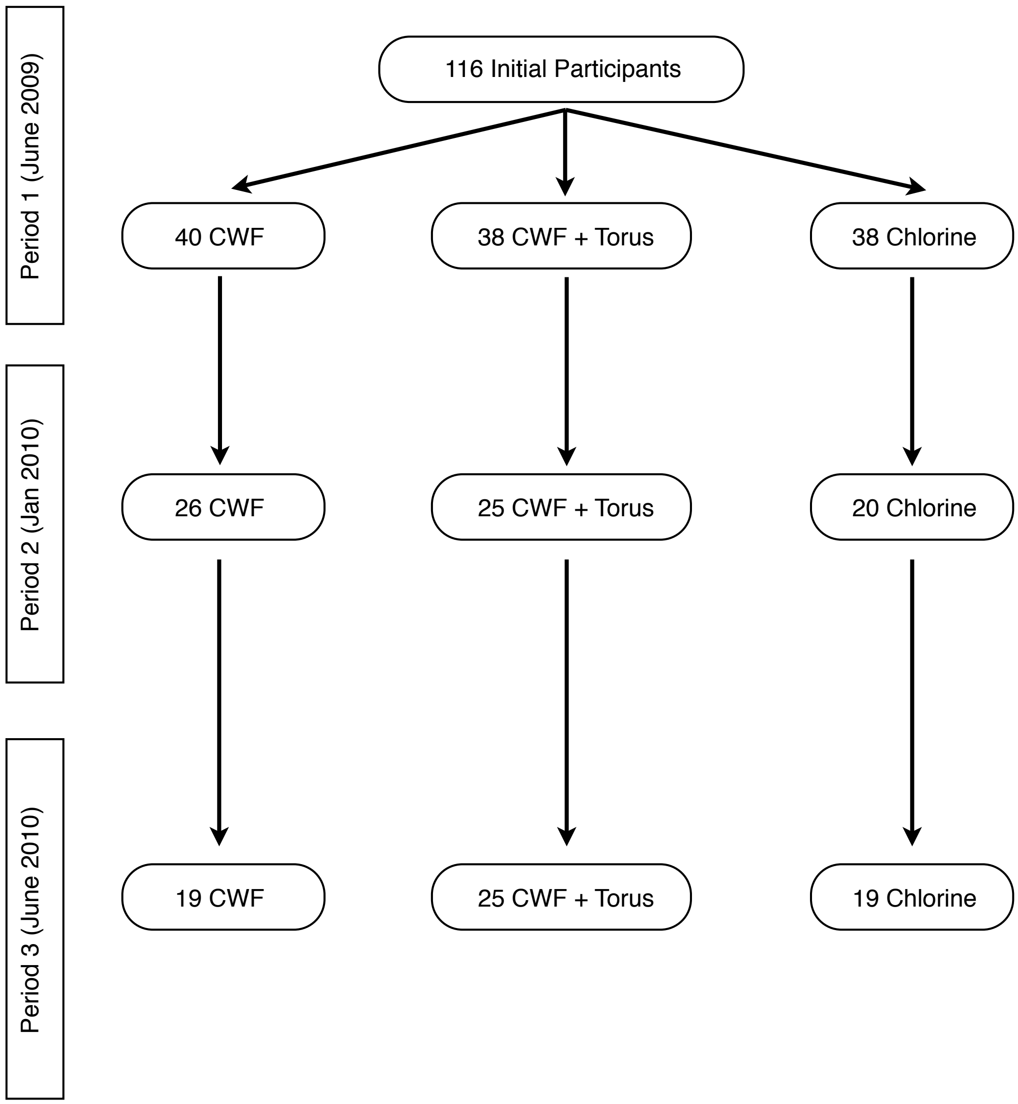

Figure 5.2: *Three Product Study Design. The 116 initial participants were recruited in June 2009 and were approximately evenly divided into the three study arms. There was significant drop out during the subsequent follow-up visits.*

5.3 Results

Although apparent mean differences in effluent water silver concentration were seen over time in Figure 5.3, these differences were not statistically significant according to the repeated measures ANOVA analysis ($F(2,34) = 0.812$, $p = 0.412$). Likewise there were no significant differences between technologies ($F(1,17) = 0.160$, $p = 0.694$). Despite the overall null results, there were mean differences between the period 1 and 2 concentrations for the CWF + torus configuration, although not the CWF according to t-test results. In these cases, silver concentration increased from 0.016 to 0.045 mg/l for the CWF + torus ($p < 0.000$) and from 0.021 to 0.033 mg/l for the CWF ($p = 0.169$). There were no mean differences for either technology between period 2 and 3. However, there was a mean difference at period 2 between the two technologies with the CWF concentration equaling 0.033 mg/l and the CWF + torus concentration being 0.045 mg/l ($p = 0.041$). These differences were not apparent at either sampling period 1 or 3 ($p = 0.377$ and $p = 0.773$ respectively).

Chlorine concentrations fell precipitously from period 1 to period 2. During the first sampling round, chlorine concentration was 1.43 mg/l on average with 100% ($n = 34$) having more than 0.4 mg/l. However, during the period 2 sampling only 65% had levels of 0.4 mg/l or higher although the average rose to 2.66 mg/l. This is due to the fact that 20% of households had concentrations in excess of 5 mg/l indicating a minority of households were possibly over-chlorinating.

Practical constraints did not allow for a standardized influent water concentrations. Instead, influent water was taken from household taps. Table 5.1 summarizes mean tap (influent) water quality for the three technologies, two bacteria types and three

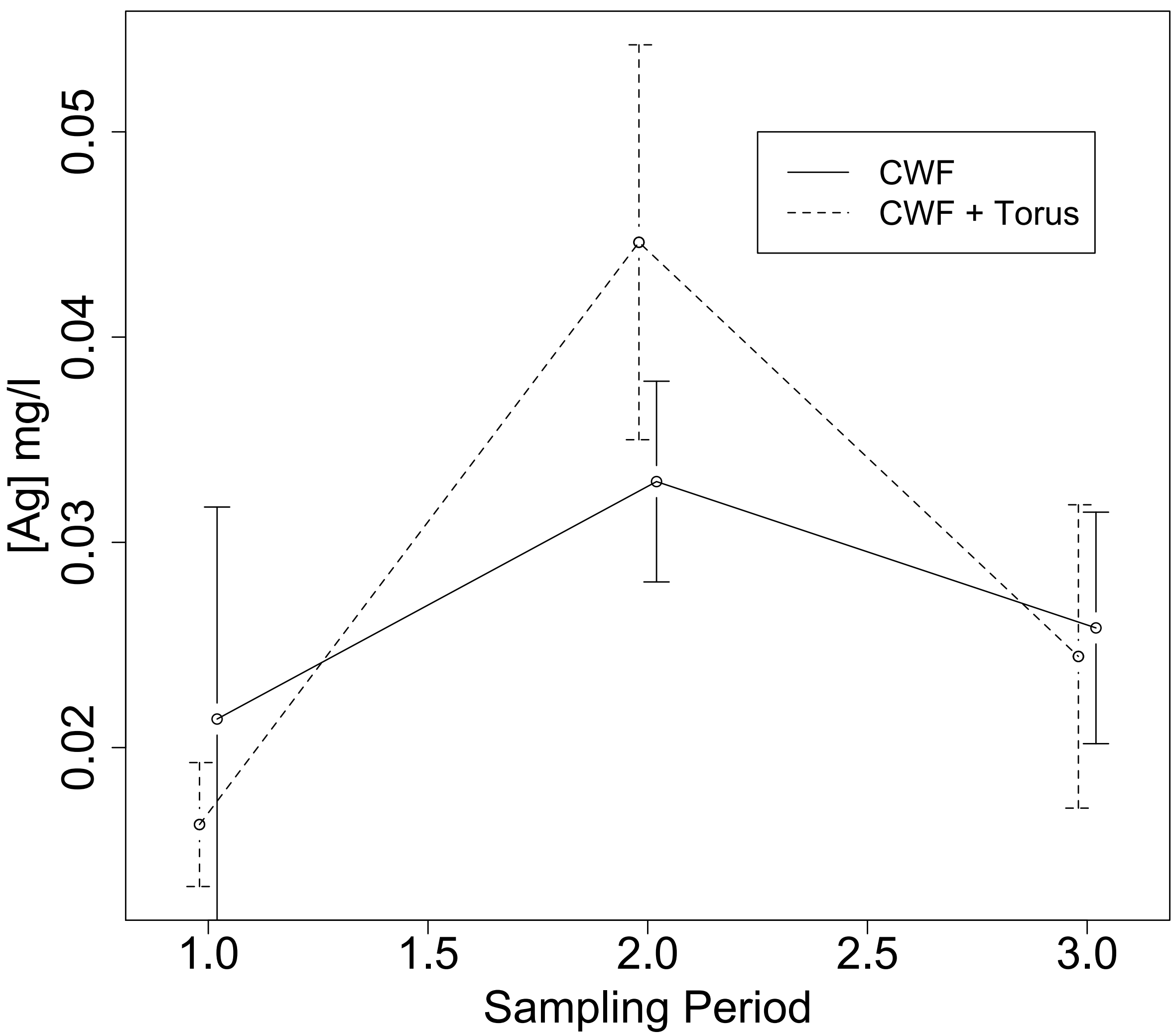

Figure 5.3: *Silver concentration for the three time periods sampled. Repeated-measures ANOVA analyses indicated there was no variation with either time or between technologies. However, a t-test indicated some variation during the period 2 sampling between the two technologies. Error bars indicate 95% CI.*

Table 5.1: *Mean tap (influent) water quality for the three sampling periods for each of the three technologies and the two bacteria types (EC (E. coli) and TC (total coliform)). P-values are the result of one-way ANOVA analyses to compare means. Results indicate that means are statistically equivalent except for the first sampling period.*

		Mean Tap (Influent) Water Quality (CFU/100mL)			
Sampling Period	Bacteria Type	CWF	CWF+Torus	Chlorine	p
1	TC	465	499	914	0.037
2	TC	525	773	651	0.746
2	EC	352	328	255	0.886
3	TC	798	632	328	0.333
3	EC	269	221	66	0.405

sampling periods. Mean tap water samples for both *E. coli* and total coliform bacteria were statistically equivalent for all three technologies for periods 2 and 3. However, they were not equivalent for period 1 ($p = 0.037$) as is seen in Table 5.1. This fact could have an effect on the period 1 results leading to possibly higher log removal rates for chlorine during this time period.

Mean log reduction values for all three technologies over the sampling periods for the two bacteria types are shown in Figure 5.4 while the same data is displayed as boxplots in Figure 5.5. The repeated-measure ANOVA analysis indicated that there were mean differences over time ($F(2,92) = 12.410$, $p < 0.000$), but not between the technologies ($F(2,46) = 0.417$, $p = 0.661$) for total coliform bacteria. However, there was no similar temporal decline for *E. coli* ($F(1,32) = 0.008$, $p = 0.930$) nor was there a difference between technologies for *E. coli* ($F(2,32) = 1.409$, $p = 0.259$).

Finally, the log removal rates for households with and without sufficient residual chlorine during the period 2 sampling was tested compared. Households with chlorine concentrations of 0.4 mg/l had significantly higher log removal rates for total coliform bacteria than those that didn't (1.79 vs 0.41, $p = 0.022$). However, log removal rates

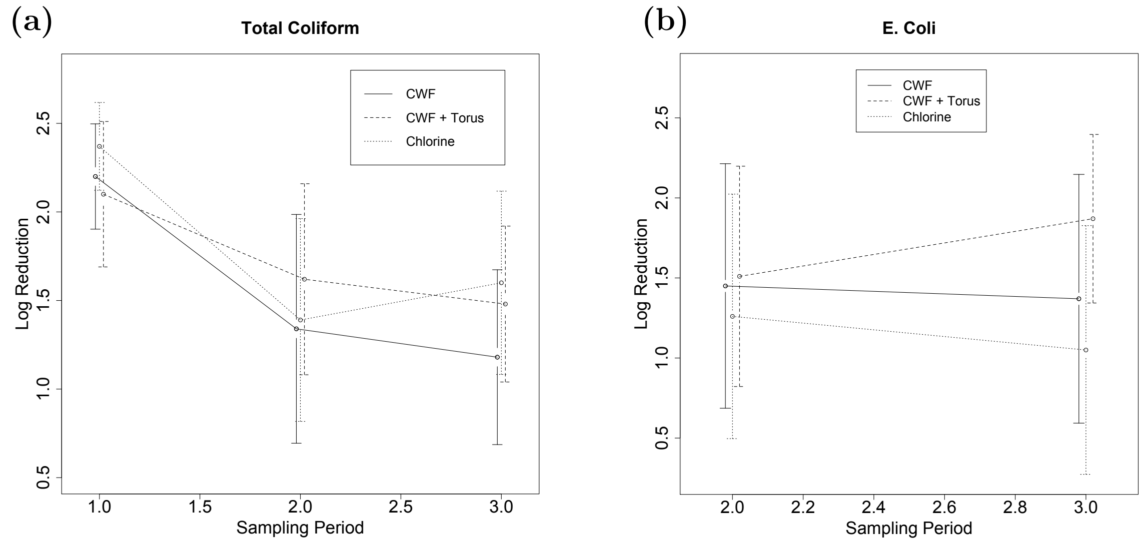

Figure 5.4: *Mean log reduction with 95% confidence intervals over the 3 and 2 sampling periods respectively for total coliform and E. coli bacteria. Repeated-measure ANOVA tests indicate a temporal decline for total coliform bacteria, but not for E. coli. No significant differences were found between technologies. Plots are consistent with temporal declines in effectiveness, but limited differences between technologies. Error bars indicate 95% CI.*

were equivalent for *E. coli* bacteria (1.09 vs 1.09, $p = 0.936$).

5.4 Discussion

We report on the longitudinal field effectiveness of three point-of-use water treatment systems. To the best of our knowledge, this is the first concurrent, comparative study of the these three interventions. Results indicate that all three technologies decline in effectiveness over time and that the toruses, as designed, are not sufficient to improve performance. Furthermore, it is evident that chlorination adherence falls precipitously over time which is something that can affect its suitability as a sustainable POU intervention.

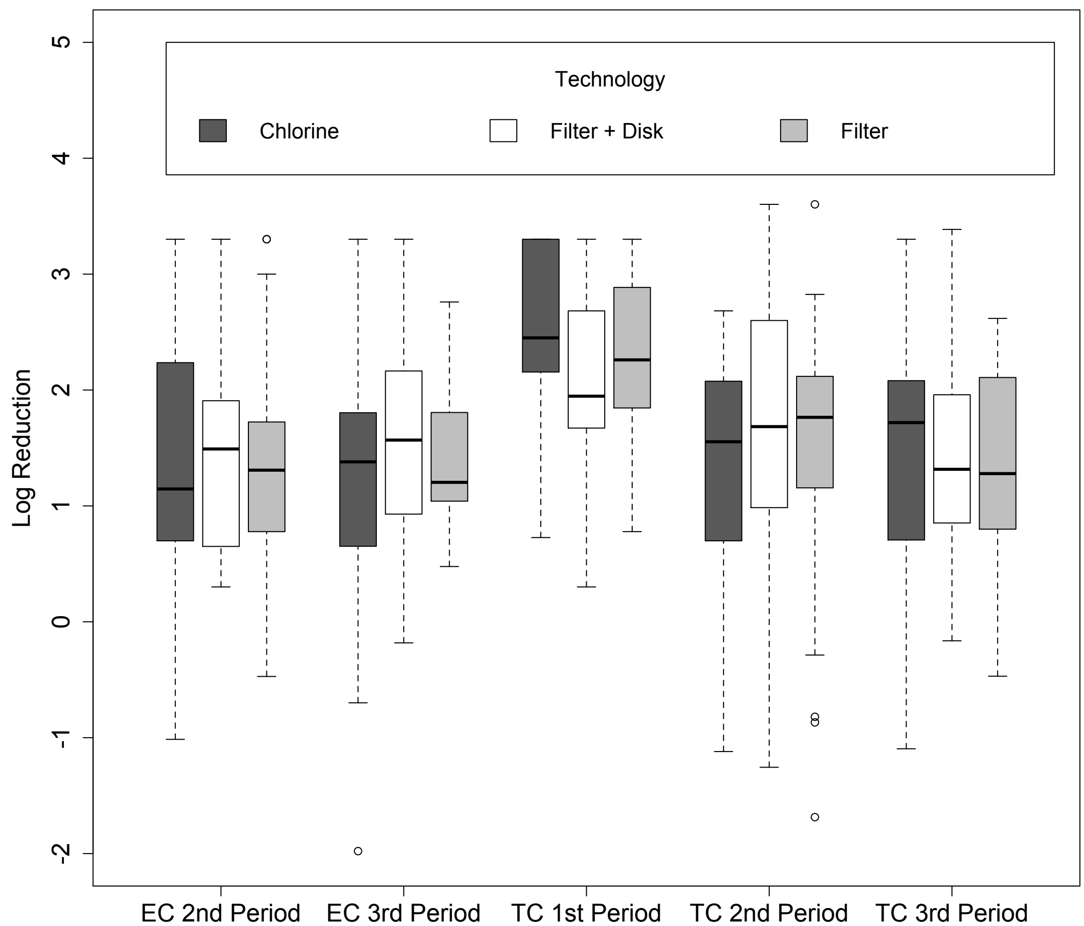

Figure 5.5: *Boxplots of log reductions for the three sampling periods for each of the three technologies and two bacteria types (EC (E. coli) and TC (total coliform)).*

The longitudinal declines in CWF effectiveness are highly consistent with those reported previously from a study conducted in South Africa (Mellor *et al.* , 2013b) and are likewise consistent with that of Hunter (2009) who found longitudinal increases in diarrhea rates for ceramic filters and other POU interventions. The high variability and negative log reduction values have likewise been seen by Brown (2007) who found that 17% of their samples had higher *E. coli* concentrations in the treated water compared to the influent water.

The relative ineffectiveness of the torus design is surprising. If designed properly such a technology should reduce the biofilm buildup quantified by others (Jagals *et al.* , 2003) and help to mitigate regrowth due to the availability of Assimilable Organic Carbon (a growth limiting substrate for coliform bacteria) in such settings (Mellor *et al.* , 2013a). One possibility is that the reservoir silver concentrations which ranged from $\sim$ 15 to 45 ppb (Figure 5.3), were insufficient to kill high concentrations of bacteria. It is notable that silver concentrations showed no variation with time and little variation between the two CWF configurations. The one exception to this was during the second sampling period when the torus design had higher levels of silver. This could have led to the statistically insignificant mean increase in log reduction for that period for both total coliform (1.42 vs 1.59, $p = 0.636$) and *E. coli* (1.41 vs 1.53, $p = 0.738$) for the CWF vs CWF+torus designs respectively. Another possibility is that reservoir contamination was not due to contamination from the reservoir itself, but rather from the ceramic filter walls or pores as was found by others in a controlled laboratory experiment (Bielefeldt *et al.* , 2009).

The reason for the lack of differences in silver concentration could be that the additional silver-impregnated surface area afforded by the torus is insufficient to effect a significant increase in lower reservoir silver concentrations. It could also be because the silver, which is simply painted on, might not last long enough on the torus to make a significant difference in silver concentrations in the reservoir. Furthermore, in the filter design, the microbes pass through the silver-impregnated ceramic which forces them into very close contact with the silver surfaces. This is apparently not occurring as efficiently in the toruses. It is likely that the toruses could be more effective if they were painted with higher concentrations of silver or had different pore sizes. It is important to note that this does not mean that lower-reservoir biofilm buildup is not occurring, or that silver-impregnated toruses are infective generally, but it does call for an improved torus design and further research to pinpoint the source of the re-contamination.

The mean log reduction values seen for the CWFs in this study of 2.20 ± 0.30 initially and declining to 1.34 ± 0.65 and to 1.18 ± 0.49 make these filters comparable to those reported previously by Brown (2007) who found log reduction values of 1-2. Likewise, the 73% reduction in the number of households with detectable levels of *E. coli* before and after chlorination for period 1 was consistent with a major meta-analysis that found an 80% reduction in the proportion of stored water samples with detectable *E. coli* (Arnold & Colford, 2007) after chlorination interventions. Although, our percentage declined to 58% during period 2, the Arnold & Colford meta-analysis relied on studies that had a median length of only 30 weeks. A recent study that compared the effectiveness of chlorination with a silver-coated porous ceramic candle element found a mean log reduction value of 1.21 for households provided WaterGuard (a dilute hypochlorite solution) while the ceramic candles provided a log reduction of only 0.91 (Albert *et al.* , 2010). Finally, it is worth noting that if the log reduction values measured in our study were to be improved to 3 or better, it could lead to improved outcomes (Mellor *et al.* , 2013b).

Our study had a number of limitations that warrant discussion. First of all, the non-uniform influent water supplies may have biased some of our results. Future studies should try to use uniform influent water supplies. Secondly, the torus design did not generally increase the silver concentration in the lower reservoir which is likely why it proved to be equally as effective at removing bacteria as the filter only design. This does not mean that the torus cannot be effective, or that biofilm layer buildup is not occurring, but it does mean that the torus needs to be redesigned to increase efficiency. That improved design should then be tested in future field trials.

5.5 Conclusions

We have conducted the first ever comparison to study the relative microbial effectiveness of 3 different water treatment devices: chlorination; CWF; and a CWF + lower reservoir torus impregnated with silver. Surprisingly, the CWF + torus design did not significantly increase silver concentrations in lower reservoirs as expected. Furthermore, the percent of households in the chlorination group with adequate residual chlorination dropped from 100% to 65% between period 1 and 2 of the study.

Log removal efficiency was highly variable and declined with time in all three cases, but there were no statistically significant differences seen between the three technologies in terms of microbial efficiency. Total coliform removal declined between period 1 and period 3 from 2.20 to 1.18 for CWF, from 2.10 to 1.48 for the CWF + torus design and from 2.37 to 1.60 for the chlorination. Likewise *E. coli* removal declined from the period 2 to period 3 sampling rounds from 1.45 to 1.37 for the CWFs, from 1.51 to 1.87 for the CWF + torus design and from 1.26 to 1.05 for the chlorination.

These results highlight the need for further study into the causes of lower-reservoir contamination in CWFs and ways to remedy this problem. Furthermore, it reiterates the need for improved follow-up and emphasis on improved adherence to water treatment regimes.

CHAPTER 6

General Discussion and Conclusions

6.1 Dissertation Summary

This dissertation attempted to develop a robust, quantitative understanding of the *complex* coliform bacteria transmission chain that leads to ECD and to investigate key mechanisms, risk factors, behaviors and intervention strategies to mitigate such transmission. This was done in three parts as discussed in Chapters 2, 3 and 4. As described in Chapter 2, the first step was a field study that sought to quantify and understand the sources and regrowth mechanisms of coliform bacteria. As part of that study there was also an extensive community survey about WASH habits and behaviors which is outlined in Appendix A.1.1. This study informed the development of the ABM which is described in Chapter 3 and Appendix A. Also a part of Chapter 3 is the sensitivity analysis that studied how different behaviors, practices and regrowth mechanisms contribute to the outcome metrics of household drinking water quality, ECD and child growth stunting. Chapter 4 outlines a study that uses the model to simulate a ceramic filter campaign. This investigation sought to answer a number of important open questions in the literature while demonstrating the flexibility and adaptability of the ABM to simulate realistic interventions.

Finally, Chapter 5 described the analysis of a longitudinal study to compare three different POU water treatment technologies including the use of a novel silver-impregnated ceramic torus designed to prevent biological contamination of the lower reservoir.

6.2 Commonalities

The conclusions of the three ABM-related studies share several commonalities in regards to the stated goal of this dissertation each of which is a contribution to the literature.

First of all, this work has demonstrated the ability of such an approach to quantitatively explore the complexities of WASH behaviors, risk factors and interventions in developing world communities. The model can reproduce field trials of single interventions, and also investigate the sensitivity of the outcome metrics to other, confounding factors and multiple, concurrently implemented interventions. It can rank risk factor importance and identify "tipping points" to inform stakeholder efforts to prioritize intervention strategies. It is also able to quickly and efficiently explore proposed interventions and examine the effects of certain interventions with minimal additional input data. It is realistic in the sense that it can explore the effects of courtesy and other biases that limit the generalizeability of many intervention-control field trials. As was shown in Chapter 4, the model is adaptable. Data sets from other regions can be introduced into the model making it a robust tool. This approach also is able to study the long-term sustainability of an intervention. This is a particularly useful aspect since fiscal, ethical and logistical constraints limit the duration of many intervention-control studies. Lastly, the method is able to geographically pinpoint regions within communities that could use additional focus although this would require additional location-specific data.

The second common element to all three chapters is that household water is frequently recontaminated after collection but before consumption and this is a primary cause of the deteriorating outcome metrics. Although such water recontamination was well-known in the literature before this study, this work was able to quantify the various risk factors contributing to this recontamination and demonstrate its effects on the outcome metrics.

A third commonality is the heterogeneity of water quality and behaviors seen throughout. For instance, the inter-household variations of water quality, biofilm layer contribution, hand-washing effectiveness, and AOC concentration seen in Chapter 2 all led to disparate outcomes in the behavior space analyses of Chapter 3. High levels of heterogeneity were likewise seen in Chapters 4 and 5 with the longitudinal microbial effectiveness curves. These high levels of variation for otherwise similar households lead one to pinpoint human behavior and its coupling with the engineered and natural environments as a primary driver of poor outcomes.

It is therefore the effects of human behaviors and their coupling with the engineered and natural environments that have proven to be the most important finding of this work along with the fact that there appear to be no silver bullets in ECD prevention. Engineered elements like municipal taps, improved water storage containers and CWFs seem to only be effective if human behaviors (broadly defined) are sufficient.

Within developing world communities, human behavior can therefore be a primary driver of the outcome metrics. In fact, this work suggests that ECD rates could be reduced to very low levels without additional engineered improvements if households in Tshapasha and Tshibvumo were to, for instance, collect water frequently and only from MT, use "narrow" neck storage containers, wash the water storage containers effectively, boil their drinking water, and use soap to wash their hands at critical times. Similarly, although ceramic filter microbial effectiveness is a factor, it appears that the human factors of consistent long-term use and frequent cleaning that have the maximal ability to drastically improve the outcome metrics. Although researchers have long known qualitatively that sustainable behaviors are important, this is one of the first approaches that can quickly quantify the effects of poor compliance for a large variety of risk factors.

Despite the fact that, for instance, it is clear through the model design that increased CWF usage would improve the outcome metrics, it was not clear what the functional relationship of CWF usage to the outcome metrics would be or how the importance of boiling frequency would compare to the numerous other risk factors. It was also not clear what intervention combinations might lead to vastly improved outcome metrics assuming imperfect compliance. This is especially true given the large and heterogenous field data set that the model relied upon and the complex model structure.

The results presented herein provide practitioners with a number of important lessons they can use to improve outcomes in such settings which were not well understood before this study. The first is the high propensity for biological regrowth and biofilm contamination. Although known qualitatively before, these results indicate that both factors can be a primary driver of the outcome metrics and are, in fact, more important that source water quality and many other risk factors. Another surprising finding is the relative lack of effectiveness of a slow sand filtration system in the communities. Researchers have long presumed the need for such a system, but these findings (which are highlighted in Figure A.13) indicate that such a system has very little impact on ECD rates. The next relevant lesson for practitioners is the fact that improvements in water quality do not always lead to large reductions in ECD rates as was seen in a number of the single parameter analyses. Previous research has indicated that multiple interventions are not terribly effective, conversely, this research indicates that multiple interventions can reduce ECD incidence to very low levels however compliance must be very high. Past studies have suggested that filters might decline in effectiveness over time, but this is the first study that suggests that the filters are almost entirely ineffective (on average) after 3 years of what is likely due to imperfect usage. This study has also shown the importance of maintaining the 3-log microbial effectiveness for point-of-use technologies to effect maximum benefits. Furthermore, this technique allows us to rank risk factor importance, understand *a priori* the effectiveness of a proposed intervention, understand biases and identify tipping points whereby given intervention levels might lead to very low ECD rates.

The policy implications for this work suggest that stakeholder efforts for WASH interventions should center around ensuring consistent long-term use of any introduced technologies along with the spreading of best practices within communities. Stakeholders should concentrate on long-term follow-up and WASH education within communities. Although this is not a new revelation, this work has demonstrated quantitatively how important the human factor can be in coupled human/engineered/natural environments.

6.3 Future Work

Although this work has contributed to the literature, there are areas for future research that can further enhance the understanding of WASH complexities:

- Coliform bacteria are just one indicator organism. Future expansions of this ABM could investigate other pathogenic bacteria, cryptosporidium, viruses or other diarrhea-causing pathogens using appropriate dose-response curves.
- Child growth is complicated by nutrition amongst other factors. Subsequent researchers might investigate the role of child nutrition as it relates to child growth stunting as an important confounding factor.
- This study focused on water chain contamination and its relationship to ECD. Future researchers might also incorporate fomites, sanitation, and other infection pathways as shown in Figure 1.1.

APPENDIX A

ABM Model Development

The model was developed using Netlogo with data obtained from community surveys. The first sections of this supplement will describe the setup routines used to initialize the model along with the community survey questions from where the input data was generated. Next are flowcharts describing in detail the model's important subroutines. Finally, expanded sensitivity and behavior space analyses are presented.

A.1 Model Development

A.1.1 Setup

Households

The first setup routine, overlays the 410 households onto a Google Maps®satellite image of the communities. Household placement is based on GPS coordinates recorded and are verified by visual inspection of the Google Map overlay. This arrangement can be seen in Figure A.1.

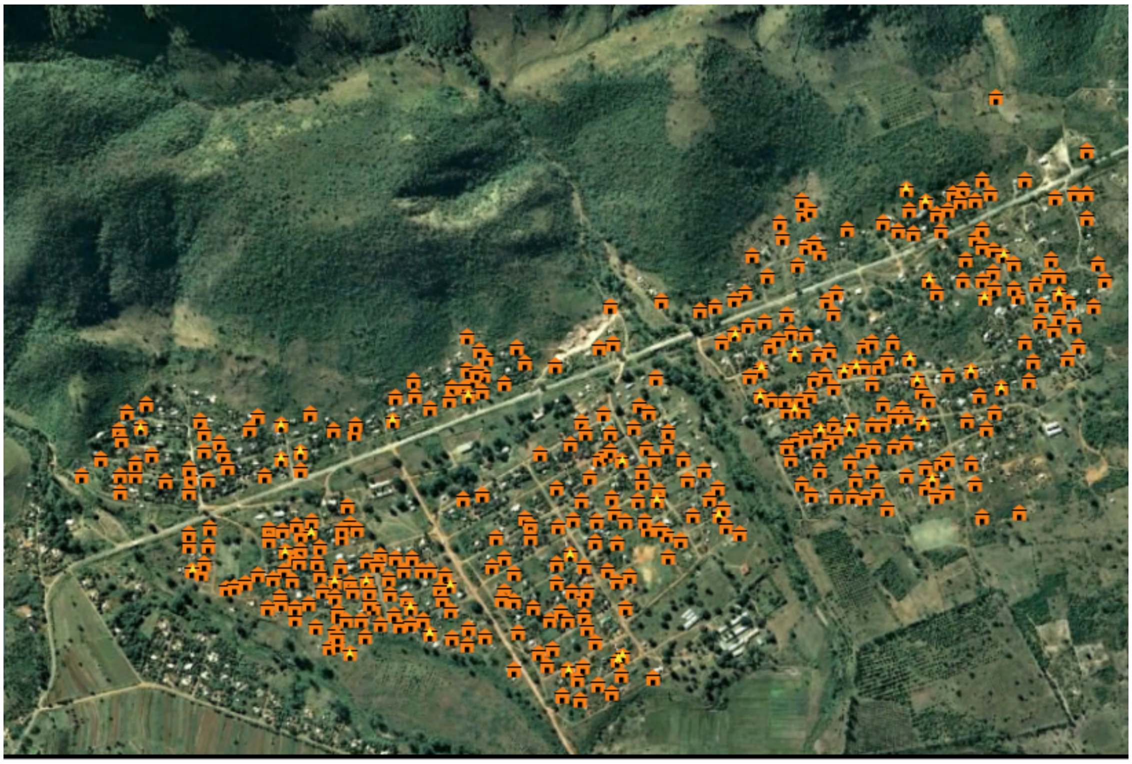

Figure A.1: *Graphical interface of the ABM in Netlogo. Households locations shown.*

Water Sources

The communities rely on three main water sources described in the main text: surface water (SW), community piped (CP) and municipal tap (MT). Each source's quality was measured during 8 months of testing as reported in previous work (Mellor *et al.* , 2012b). These data are stored in the model and accessed during the child-drink subroutine below. Histograms of the water quality data for all three sources is given in Figure A.2.

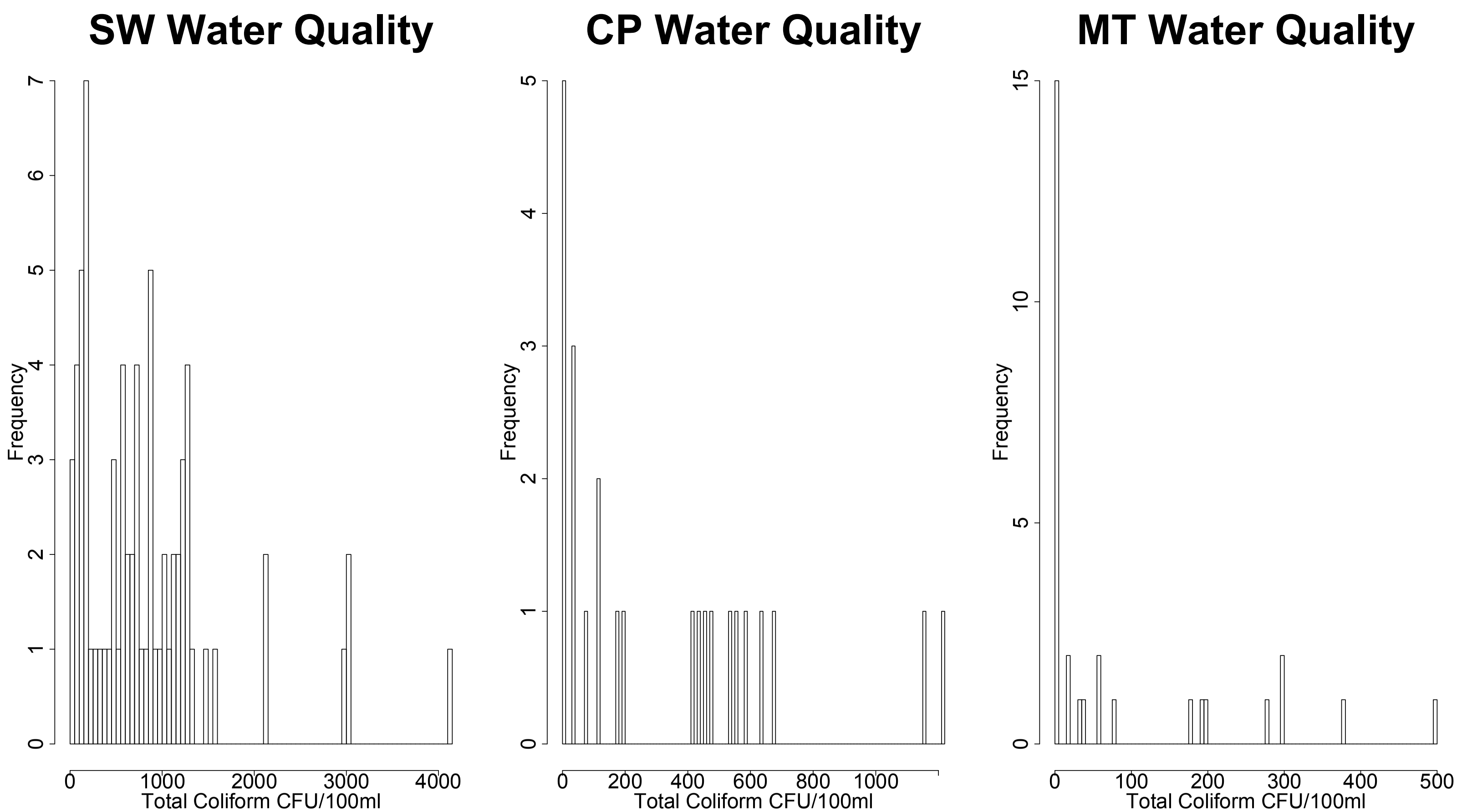

Figure A.2: *Histograms of water quality measurements used in the ABM for the three main water sources: surface water (SW), community piped (CP) and municipal tap (MT). Data indicate large inter and intra-monthly variability in all three sources.*

Water Storage Containers

Biological testing of household water storage containers was reported on previously (Mellor *et al.* , 2012b). Residents typically used two different storage container types 'narrow neck' and 'wide neck'. Each storage container has an associated biofilm layer contribution as discussed in the main text. Houses with 'wide neck' style containers must insert their hands and scoop water out which will contaminate the water. The characteristics of surveyed households are then shared to surrounding households by having each surrounding household seek out surveyed households in a progressively larger radius until they find a household with the relevant values. Histograms of these contributions is shown in Figure A.3.

Water Collection Intervals

Residents were queried several different ways about their water collection habits. First, they were asked what their primary and secondary water sources were. They were then asked the basic question "How often do you collect water?" on two different occasions. Next, they were asked to keep a daily log for 4 weeks detailing each time they collected water. These data were then converted into collection intervals. The lowest and highest reported values are used in the ABM. Finally they were asked "How many days can you wait until you need to use secondary source?" which is used as the maximum number of days households will take before they revert to secondary water sources. As with the other metrics, households that were not surveyed take on the characteristics of nearby households. Histograms of collection frequency are shown in Figure A.4.

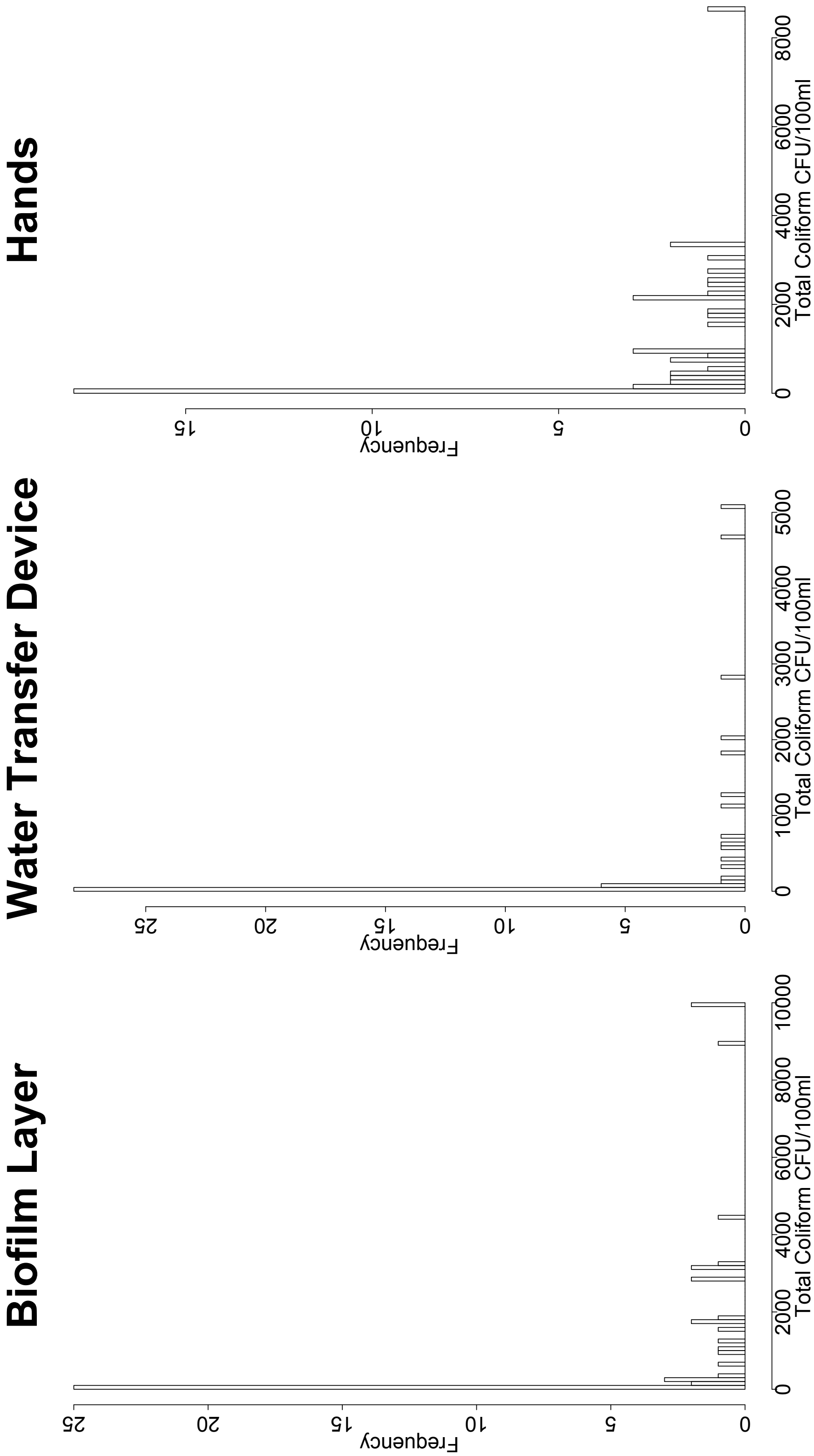

Figure A.3: *Histograms of biofilm layer* (HHS_i)*, water transfer device and hand contributions to water contamination. All three show large heterogeneity and strong potential as large contributors to household water quality deterioration. Water transfer device and hand contributions have the potential to contaminate 'wide neck' storage containers, but not 'narrow neck' ones.*

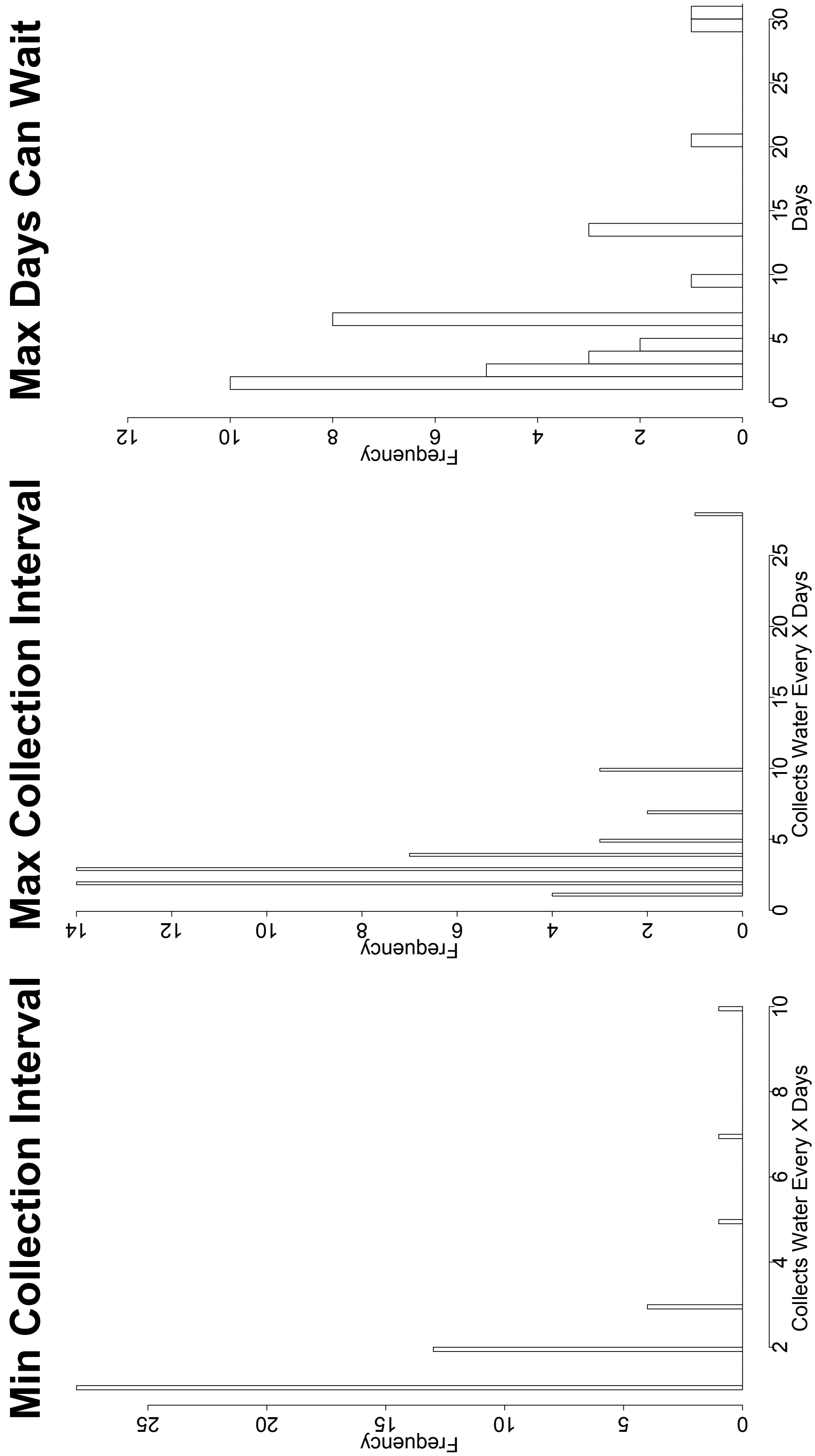

Figure A.4: *Histograms of collection frequency. Minimum and maximum collection intervals based on the minimum and maximum values reported by households during surveying. Maximum days can wait based on community survey.*

Boiling Frequency

Residents reported that they occasionally boil their drinking water to treat it, other treatment methods such as chlorination are not common. Several questions were asked to ascertain resident's boiling frequency including "When did you last treat your water?", "In a given week, how many times do you treat your water?", "In a given day, how many times do you treat your water?", "How frequently do you drink water that has not been treated?". In addition, participants filled out a daily log of their practices. These metrics were all converted to boiling intervals and the minimum and maximum values for each household were used for the ABM. Households not surveyed obtained the boiling intervals of nearby households. Histograms of boiling intervals are shown in Figure A.5.

Hand-Washing Frequency

Similar to the other metrics, hand-washing was measured in the communities using several questions. These include the questions "In the last 24 hours when did you last wash your hands?", "In the last 24 hours, how many times did you wash your hands?" Participants were also asked to fill out daily logs of hand-washing activities. The minimum and maximum responses were used for the ABM. Households not surveyed took on frequencies of nearby households. Histograms of hand-washing frequency are shown in Figure A.6.

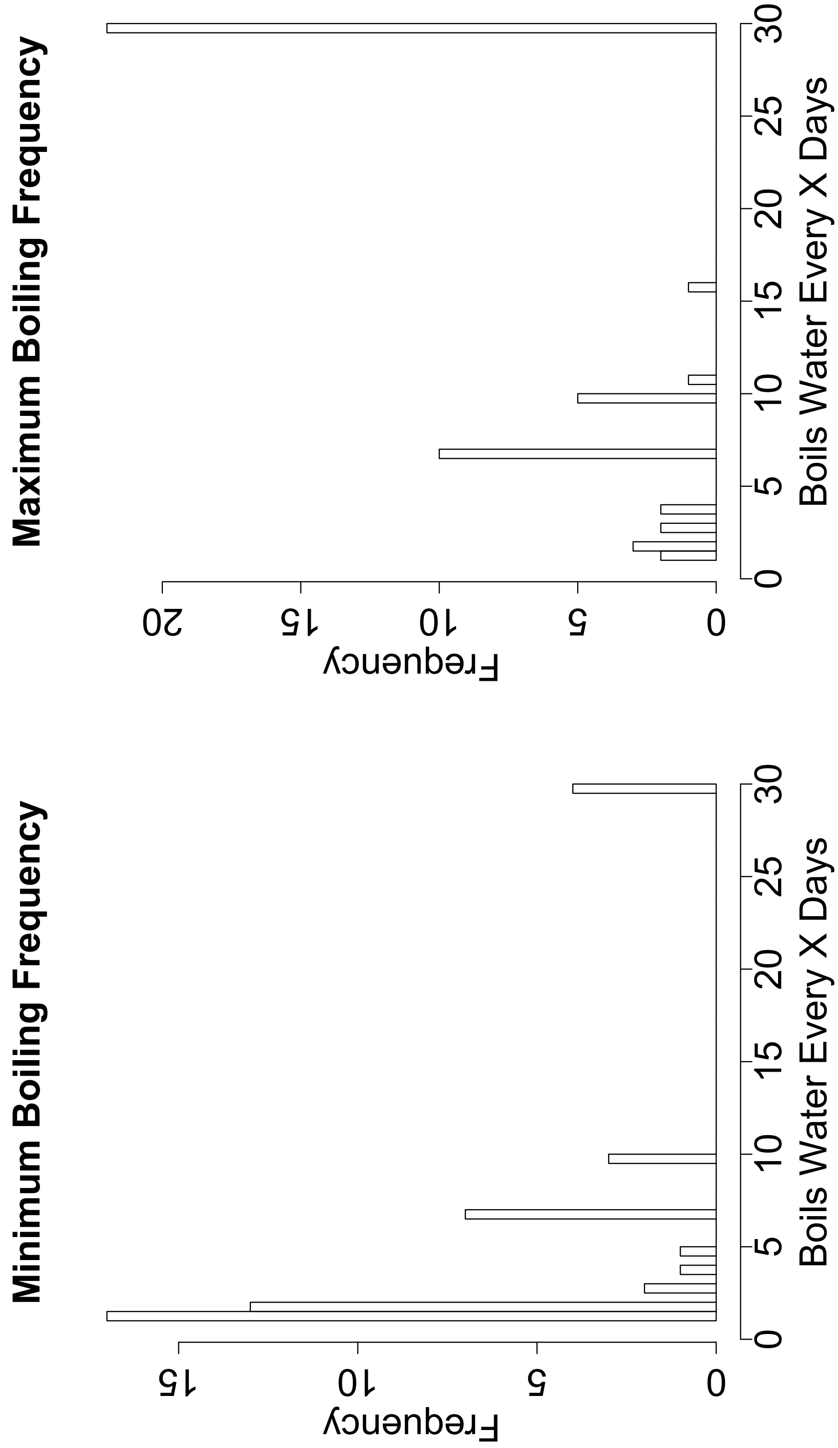

Figure A.5: *Histograms of boiling frequency. Minimum and maximum boiling intervals based on the minimum and maximum values reported by households during surveys.*

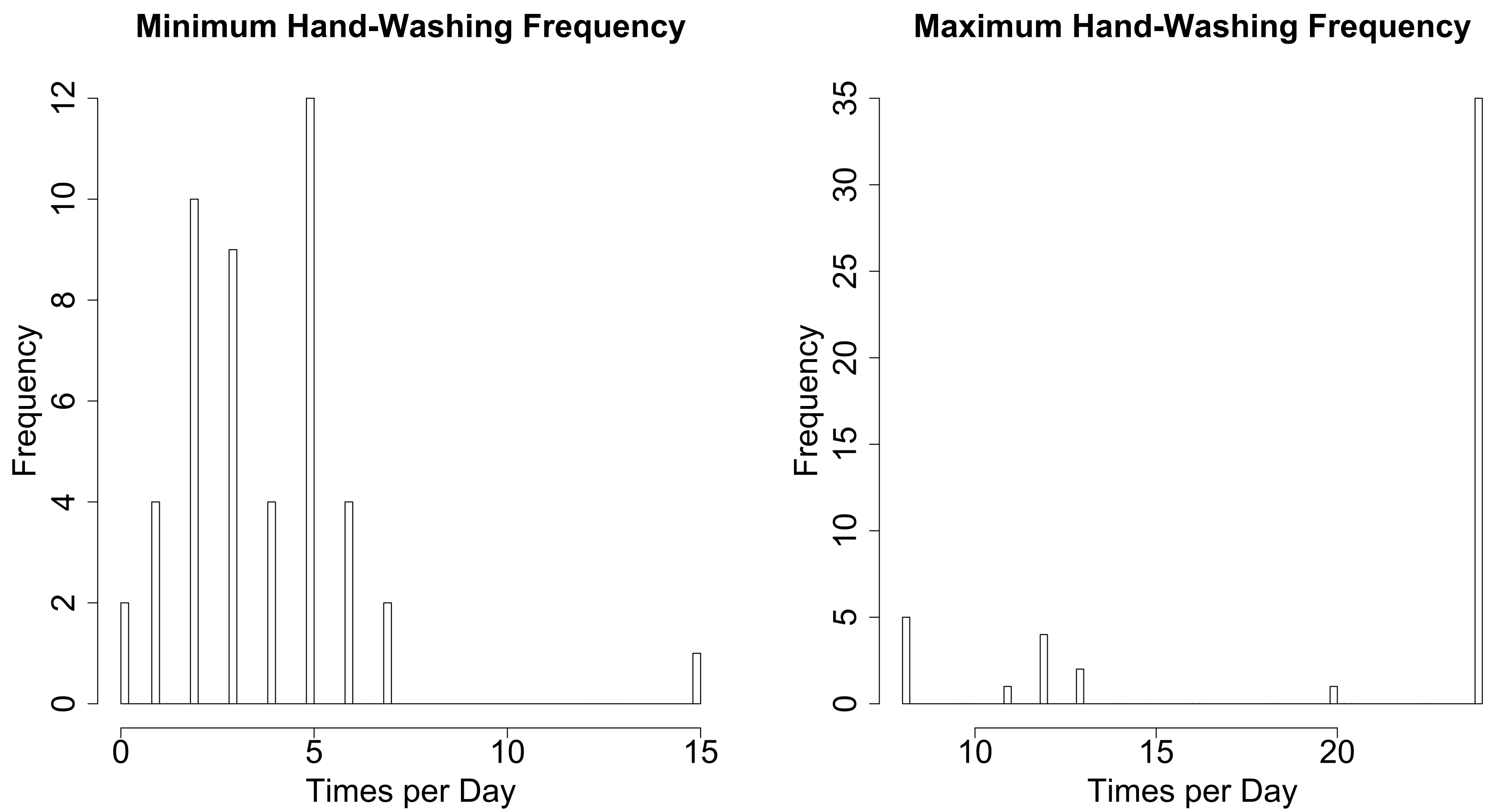

Figure A.6: *Histograms of hand-washing frequency in terms of the number of times per day. Frequencies based on minimum and maximum values reported by households during surveys.*

HAZ

As described in the main text, HAZ scores were calculated by taking the HAZ difference between four months before and four months after an ECD case. Likewise, the calculation was also performed for those with two or more ECD cases during that 8-month period. The ages and HAZ differences are input into the model. When a ABM child gets ECD, they are then assigned a HAZ reduction score of the individual child closest in age to themselves.

A.2 Model Routines

Collect Water

The first sub-routine for the model details the water collection, bacteria regrowth, biofilm layer contribution and container cleaning. Residents of the two communities were asked what sources they used and how frequently those sources worked. Results indicate that CP works 45.4% of the time while MT works 68.4% of the time. A flow-chart describing the process is shown in Figure A.7.

The experimental protocol reported previously (Mellor *et al.* , 2012b) involved introducing 500 mL of sterilized water into empty water storage containers, swirling vigorously and then testing the water to determine the coliform bacteria concentration (HHS_i) (Mellor *et al.* , 2012b). This approximates the ability of the biofilm-layer bacteria to contaminate water. However, the ability of a given water container to contaminate a larger volume of water is uncertain. To approximate this process the volume of water in a given water container (V_i) is calculated stochastically (continuous uniform distribution) between 0.5 and 20 L, which is the range of volumes measured in the community. HHS_i is then diluted according to the following formula where v_i is a stochastic (continuous uniform distribution) variable between 0.5 L (amount of water used in the experiment) and V_i.

$$hhs_i = HHS_i \times \frac{0.5L}{v_i} \tag{A.1}$$

This dilution factor ranges in value from 0.025 to 1. WQ_i is not allowed to go below hhs_i during storage.

Water transfer devices are typically cups or ladles used to scoop water from the 'wide neck' storage containers used by approximately half of the households. There is also a significant amount of coliform bacteria associated with a person's hands. If a household has a 'wide neck' storage container then WQ_i is not allowed to go below the sum of these two contamination sources diluted by a factor of $\frac{0.5L}{V_i}$ since those experiments were likewise carried out in 0.5 L of water. Those with 'narrow neck' containers have no such contamination sources.

Treat and Drink Water

The next sub-routine involves the treatment and drinking of water and is summarized in Figure A.8.

Calculate Height

Finally, children grow according to the sub-routine shown in Figure A.9 and detailed below.

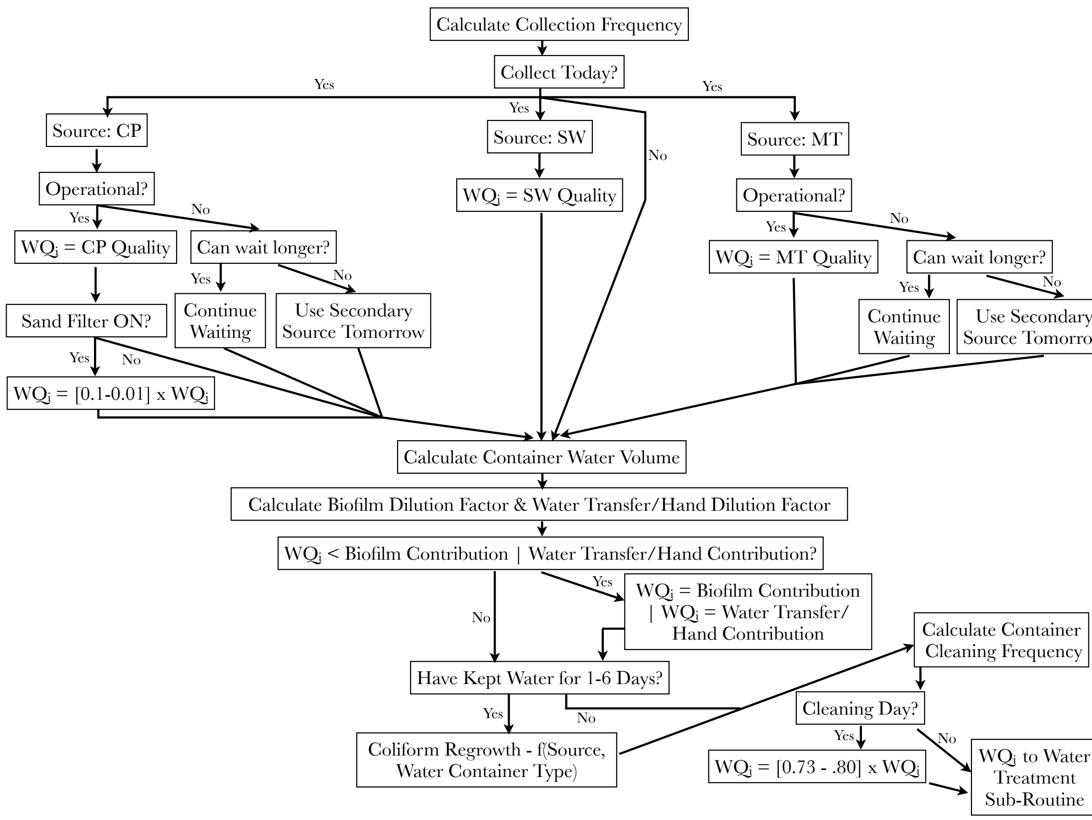

Figure A.7: *Flow chart of the Collect Water Sub-Routine. This flow chart is repeated for each household for each day of the simulation. Square brackets indicate values that are stochastically varied between minimum and maximum values over a continuous uniform distribution. SW - surface water, CP - community piped, MT - municipal tap,* WQ_i *daily water quality of* i^{th} *household.*

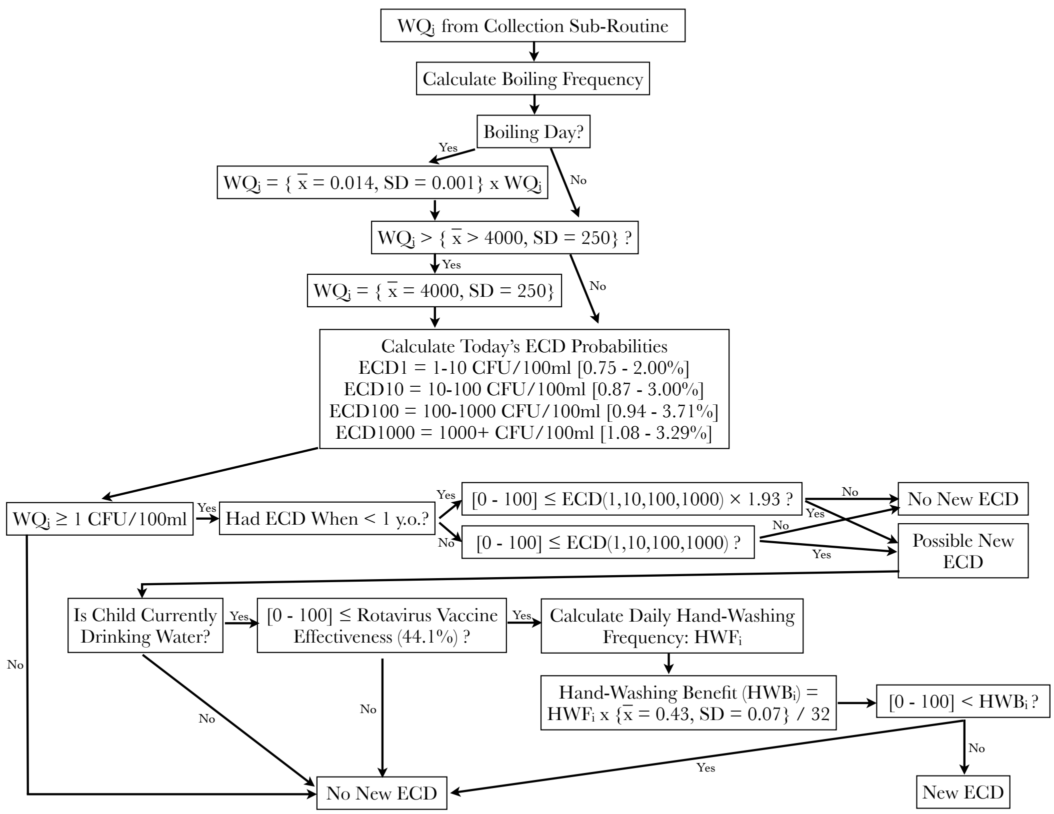

Figure A.8: *Flow chart of Water Treatment and ECD Calculations. The treatment portion occurs for each household each day. The ECD Calculation portion occurs for each child each day. Curly brackets indicate a variable that is stochastically varied according to a normal distribution with mean and standard deviations indicated. Square brackets indicate values that are stochastically varied between minimum and maximum values over a continuous uniform distribution. Parentheses indicate a functional relationship, i.e. the probability of getting ECD is a function of* WQ_i.

The HAZ data are incorporated into the model by using data for the individual Mal-ED child closest in age to the individual ABM model child. This can account for possible HAZ reduction age differences. The daily child growth increment ΔH is calculated considering that the daily HAZ difference (±4 month HAZ reduction values divided by 8 months), ΔHAZ, is as follows in Equation A.2:

$$\Delta HAZ = \frac{H_{age} - H^S_{age}}{SD_{age}} - \frac{H_{age+1} - H^S_{age+1}}{SD_{age+1}} \tag{A.2}$$

In this equation, H is the height, the subscript *age* is the current child age, SD is the age standard deviation (De Onis, 2006), the superscript S indicates the WHO standard median values and the +1 indicates the subsequent day. Rearranging and introducing the daily growth increment $\Delta H = H_{age+1} - H_{age}$ for children with ECD:

$$\Delta H = H^S_{age+1} - SD_{age+1}\left(\Delta HAZ - \frac{H_{age} - H^S_{age}}{SD_{age}}\right) - H_{age} \tag{A.3}$$

An ABM child with a 'single' ECD case then grows according to Equation A.3 which is a function of the ΔHAZ of the Mal-ED child of the most similar age who had a 'single' case of ECD. If a child has a 'double' ECD case they similarly grow at the ΔHAZ of the most similar age Mal-ED child who had a 'double' ECD case.

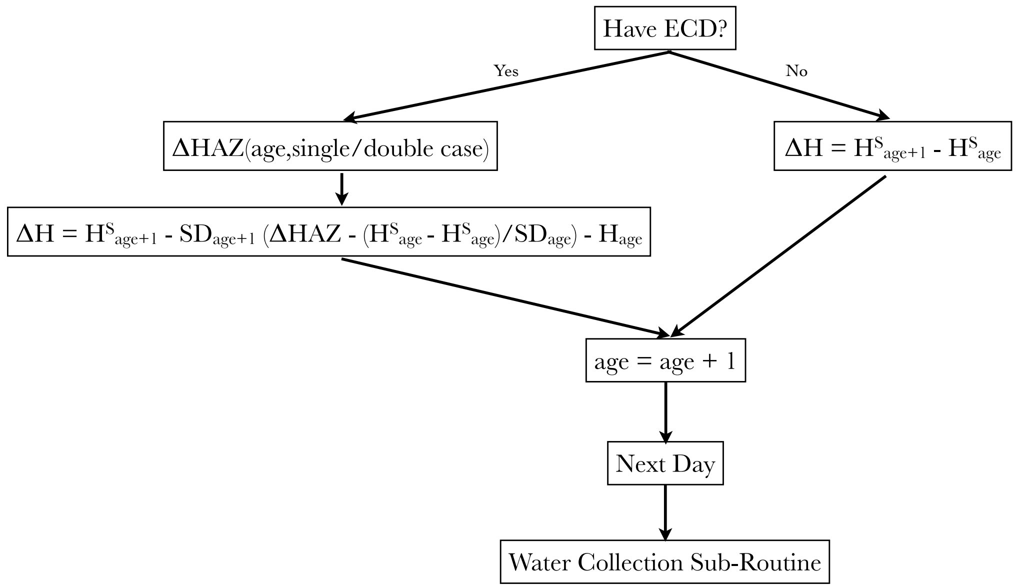

Figure A.9: *Flow chart of Height Calculations. This sub-routine is performed for each child each day.*

A.3 Sensitivity Analysis

The sensitivity of the model to two parameters was tested. These parameters include the length of growth-stunting (set at 8 months) and the dose-response relation between coliform bacteria and ECD incidences summarized in Figure 3.3.

For the growth-stunting analysis, the growth-stunting period was varied between 120 and 360 days. Over this interval, mean HAZ_2 values varied between -1.41 and -1.61 as can be seen in Figure A.10 indicating a moderate variation over those growth stunting periods. However, since the growth stunting period is based on field measurements using data from the Mal-ED project, this variation is acceptable.

The second analysis introduced multiplicative factors between 0.5 and 1.5 of the stochastically varied (continuous uniform distribution) dose-response relationship shown in Figure 3.3. These factors did vary ECD rates from 3.8 to 13.3 mean cases and HAZ_2

values from -1.23 to -1.74 as can be seen in Figure A.11. Despite this sensitivity, the overall qualitative conclusions seen in, for instance, boiling frequency, remain identical as is seen in Figure 3.5. In all five factors tested, boiling frequency must be preformed daily to be effective.

A.3.1 Additional Single Parameter Behavior Space Tests

The single parameter behavior space analysis was conducted for the four scenarios in the main text. In addition, eleven other major parameters were tested and are included here for reference.

Figure A.12 summarizes results from five different analyses related to water storage, cleaning, biological regrowth and hand-washing. The percent of the community with 'narrow neck' water containers has an effect on median daily water quality ($F = 16{,}872$, $p < 0.001$), mean total ECD cases ($F = 2176.9$, $p < 0.001$) and HAZ_2 ($F = 233.84$, $p < 0.001$). The effects on WQ_i are significant over this range, but the effects on mean total ECD cases and HAZ_2 are not great. However, it is notable that the multiple scenario analysis found the percent 'narrow neck' was a strongly linked to optimal HAZ_2 values. Residents who use 'narrow neck' containers do not need to use water transfer devices and their hands to not contaminate the water when they drink it. Furthermore, biological regrowth is less in such containers.

The water transfer device contribution had an effect on household water quality and child health. Variation statistical significance is as follows: median WQ_i ($F = 9251.5$, $p < 0.001$), mean total ECD cases ($F = 161.37$, $p < 0.001$), and HAZ_2 ($F = 23.644$, $p < 0.001$). Although a rather large difference is seen in terms of WQ_i, there were small differences in mean ECD cases and HAZ_2 indicating that the water transfer device

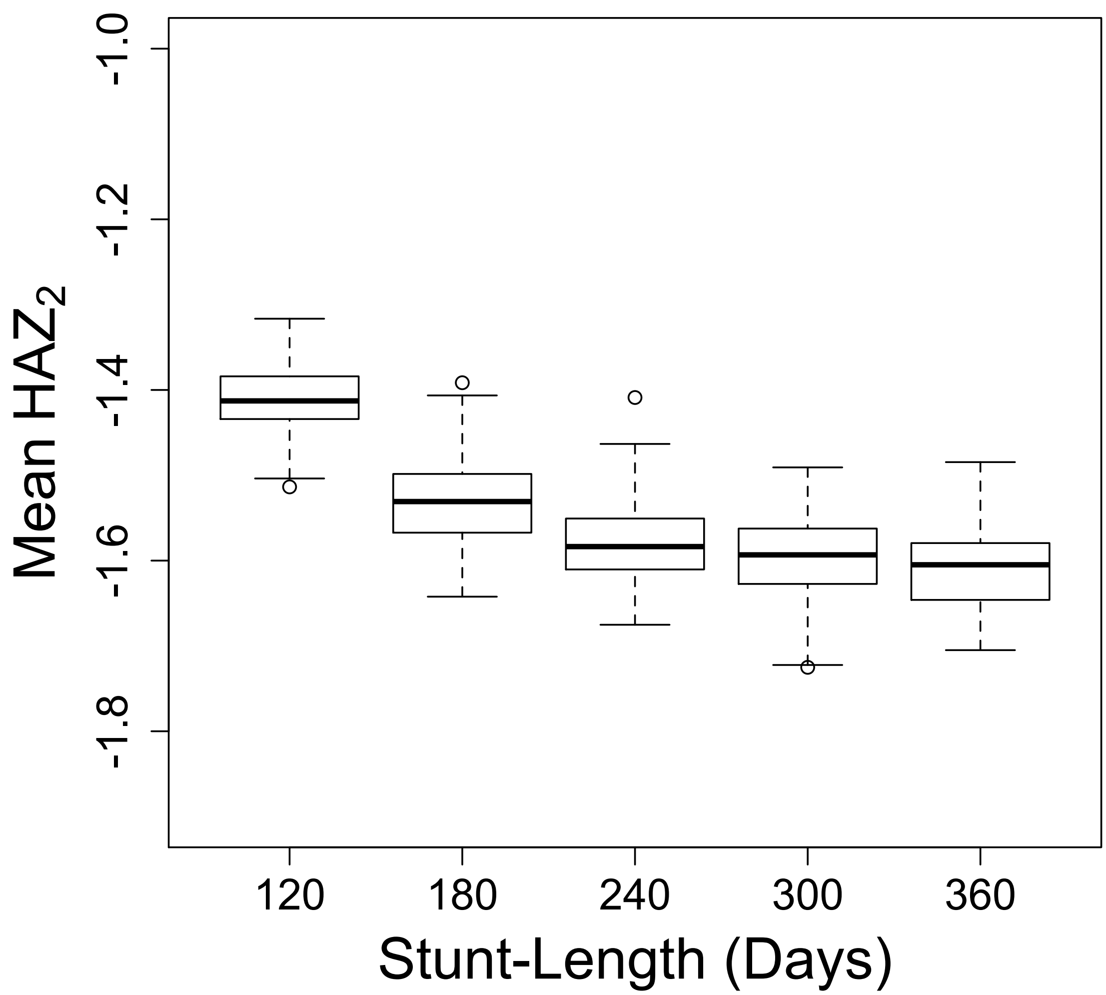

Figure A.10: *Sensitivity analysis of stunt-length variable. Data indicate a moderate associate between the duration of growth stunting and final* HAZ_2 *scores.*

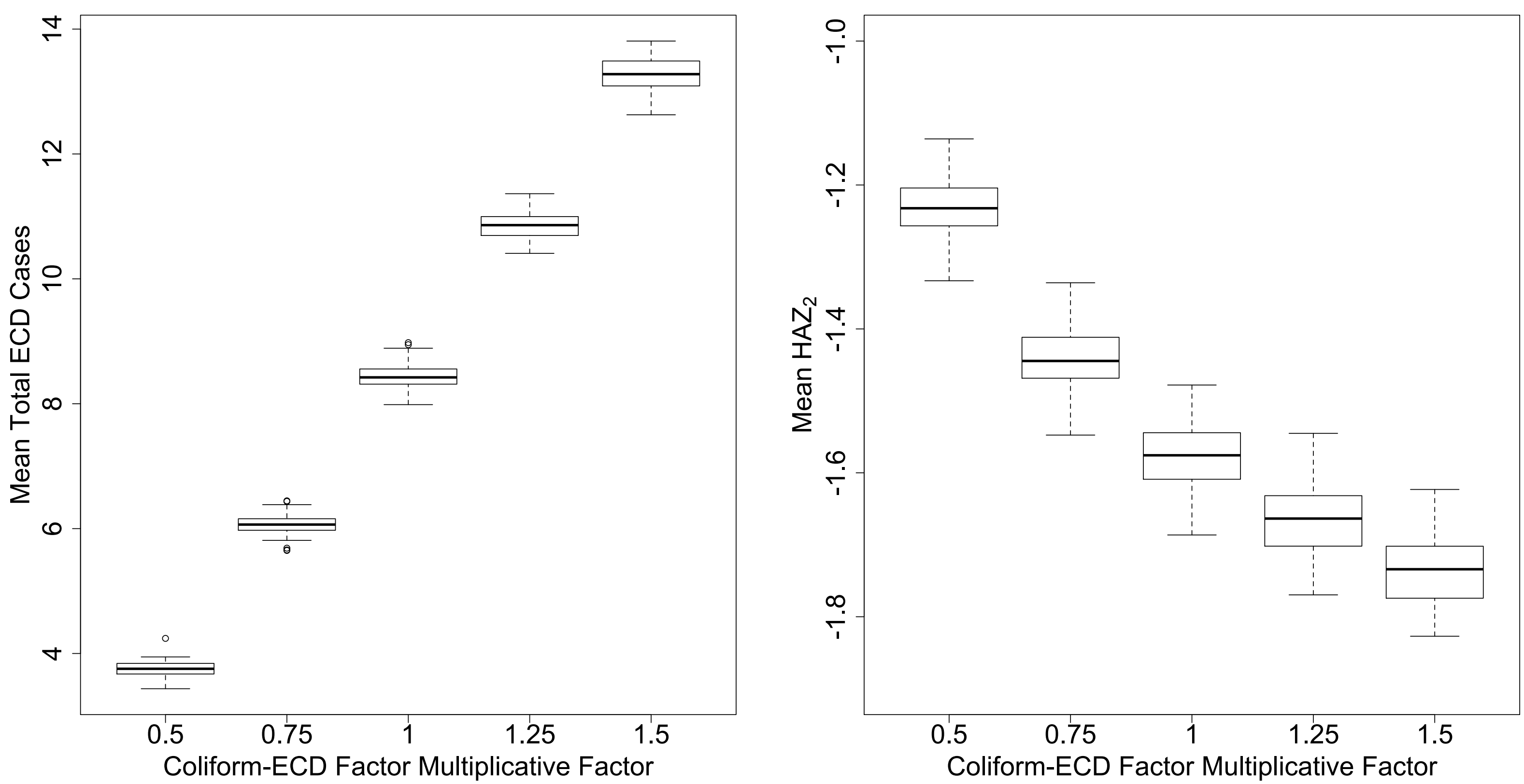

Figure A.11: *Mean EDC cases and HAZ_2 scores for coliform-ECD factor sensitivity analysis. Results indicate that multiplying the stochastically (continuous uniform distribution) varied dose-response functions do change both ECD cases and HAZ_2 scores.*

contribution is relatively small. This may be due to the fact that only about 50% of residents use the 'wide' mouth containers that require water transfer devices.

Coliform regrowth was also a statistically significant contributor to median WQ_i (t = 159.7604, $p < 0.001$), mean total ECD cases (t = 12.8521, $p < 0.001$) and HAZ_2 (t = -2.2125, p = 0.028). Coliform regrowth has a large impact WQ_i and a smaller impact on mean total ECD cases and HAZ_2. Despite the relatively small differences seen here, coliform regrowth does play a larger role for the collection frequency experiments and is higher in 'wide neck' containers.

Cleaning frequency statistically affected median WQ_i (F = 1329.9, $p < 0.001$) and mean total ECD cases (F = 63.508, $p < 0.001$), but not HAZ_2 (F = 2.8892, p = 0.090). Cleaning everyday has a small effect on median WQ_i, but little effect on either mean total ECD cases and no effect on HAZ_2. This is likely because the cleaning effectiveness as measured in the communities is very low. If community members cleaned their storage containers vigorously this metric would likely be far more important.

Hand-washing does not statistically affect median WQ_i (F = 2.241, p = 0.1350) but it does affect mean total ECD cases (F = 42,371, $p < 0.001$) and HAZ_2 (F = 1546.8, $p < 0.001$). Since hand-washing is not directly linked to the water chain, there was no variation in WQ_i. The other two outcome variables, mean total ECD incidences and HAZ_2 showed significant declines.

CP water quality statistically affects median WQ_i (F = 3607.1, $p < 0.001$), mean total ECD cases (F = 405.4, $p < 0.001$) and HAZ_2 (F = 135.10, $p < 0.001$). WQ_i deteriorated significantly with CP water quality. This sensitivity of WQ_i to source water is somewhat surprising given previous results (Wright *et al.* , 2004). Mean total

ECD cases and mean HAZ_2 scores only changed by large amounts when CP water quality is optimal.

SW water quality statistically affects median WQ_i ($F = 243.25$, $p < 0.001$), mean total ECD cases ($F = 44.413$, $p < 0.001$) and HAZ_2 ($F = 11.406$, $p = 0.001$). Surface water is generally a secondary water source for most community members, therefore although it is statistically significant it is not strongly correlated to WQ_i and therefore mean ECD cases and HAZ_2 in this scenario.

The percent coverage of the CP and MT water systems was varied from 0 to 100% to study the potential effects of community members switching to more desirable water sources. In both cases the remainder of the households use an equal distribution of other sources. The results indicate that WQ_i varies ($F = 480.03$, $p < 0.001$) as do mean total ECD cases ($F = 496.74$, $p < 0.001$) and HAZ_2 ($F = 162.87$, $p < 0.001$) in both cases. These results are consistent with the CP and MT results that show that improved source water quality can improve WQ_i.

CP operational frequency statistically affected median WQ_i ($F = 2258.1$, $p < 0.001$), mean total ECD cases ($F = 27.830$, $p < 0.001$) but not HAZ_2 ($F = 2.6968$, $p = 0.101$). Despite the statistical significance, CP operational frequency is not strongly correlated to WQ_i, mean total ECD cases or HAZ_2. This is especially surprising given the trends seen in the collection frequency experiment. This is likely due to the fact that after the first 72 hours, biological regrowth levels off and so water storage time is less important after this initial period (Mellor *et al.* , 2012b). This, coupled with the fact that residents usually only want to collect water every several days is likely the reason for the relative insensitivity of the model to this parameter.

MT operational frequency also showed statistical variation of median WQ_i (F =

515.17, $p < 0.001$) but not mean total ECD cases ($F = 2.5888$ $p = 0.108$) or HAZ_2 ($F = 0.1143$ $p = 0.735$). These results are largely similar to the CP results above with similar reasoning.

SSF status led to statistical variation of median WQ_i ($t = -74.3327$, $p < 0.001$), mean total ECD cases ($t = -10.6801$, $p < 0.001$), and HAZ_2 ($t = 3.3165$, $p = 0.001$). WQ_i did vary significantly, but there was less absolute variation in either mean total ECD cases or HAZ_2 scores.

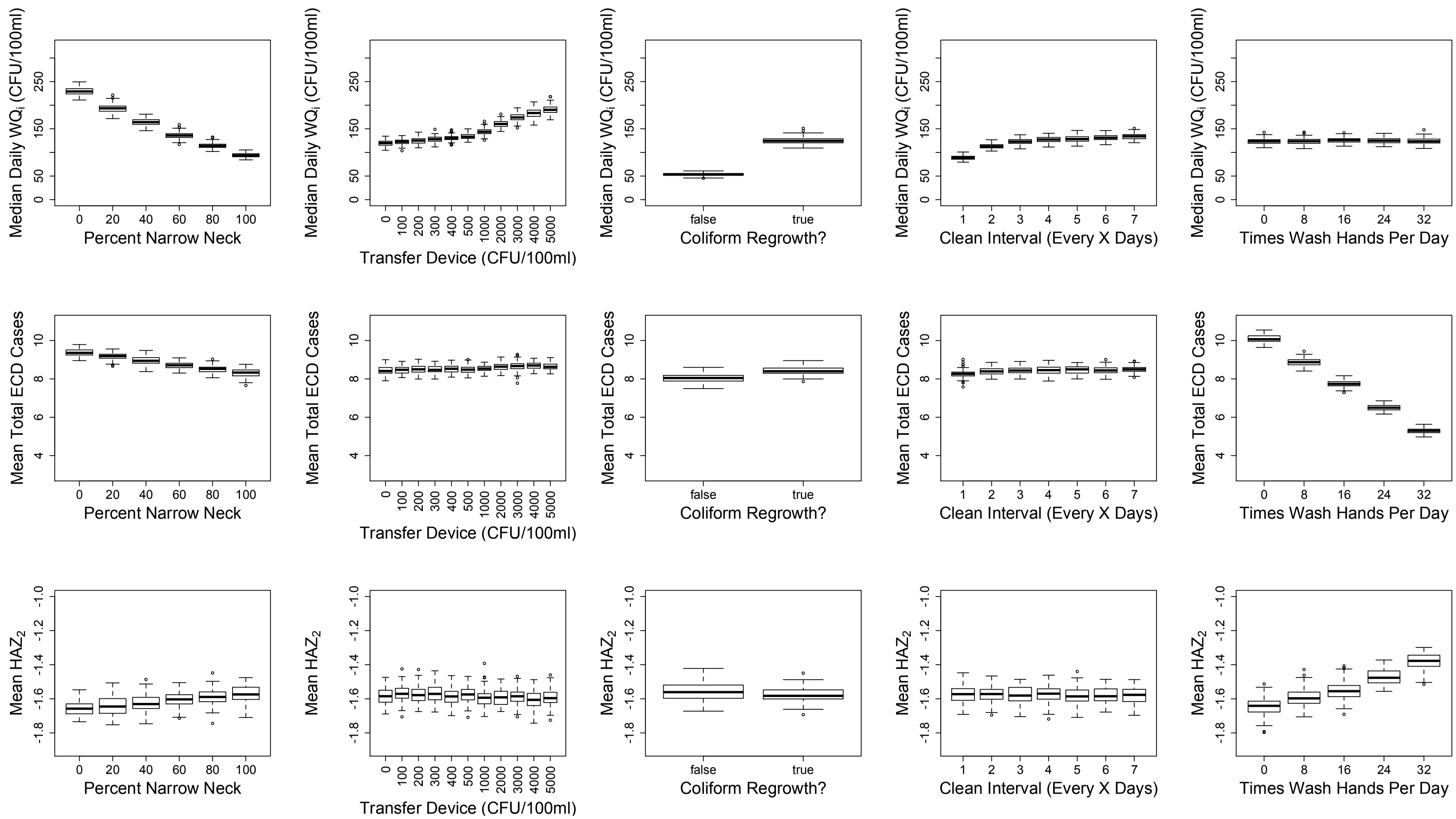

Figure A.12: *Behavior space analyses for five different important model parameters. Results summarized in terms of median daily WQ_i, mean total ECD cases, and mean HAZ_2. Percent narrow neck, refers to percentage of the community that has 'narrow neck' water storage containers as opposed to the 'wide neck' variety. Transfer device refers to coliform contamination from water transfer devices, which are typically cups or ladles. Note the non-linear x-axis which is representative of field measurements. The coliform regrowth experiment showed the effects of biological regrowth in water storage containers. The cleaning interval refers to the interval in which households clean their water storage containers, with that effectiveness being determined by field measurements. The times wash hand per day varies from 0 to 32, with 32 times per day being considered optimal. Median daily WQ_i varies for most experiments, but these variations do not lead to large variations in ECD cases or mean HAZ_2. Exceptions include the percent 'narrow neck' and hand-washing frequency, but of which showed some improvement with improved behaviors.*

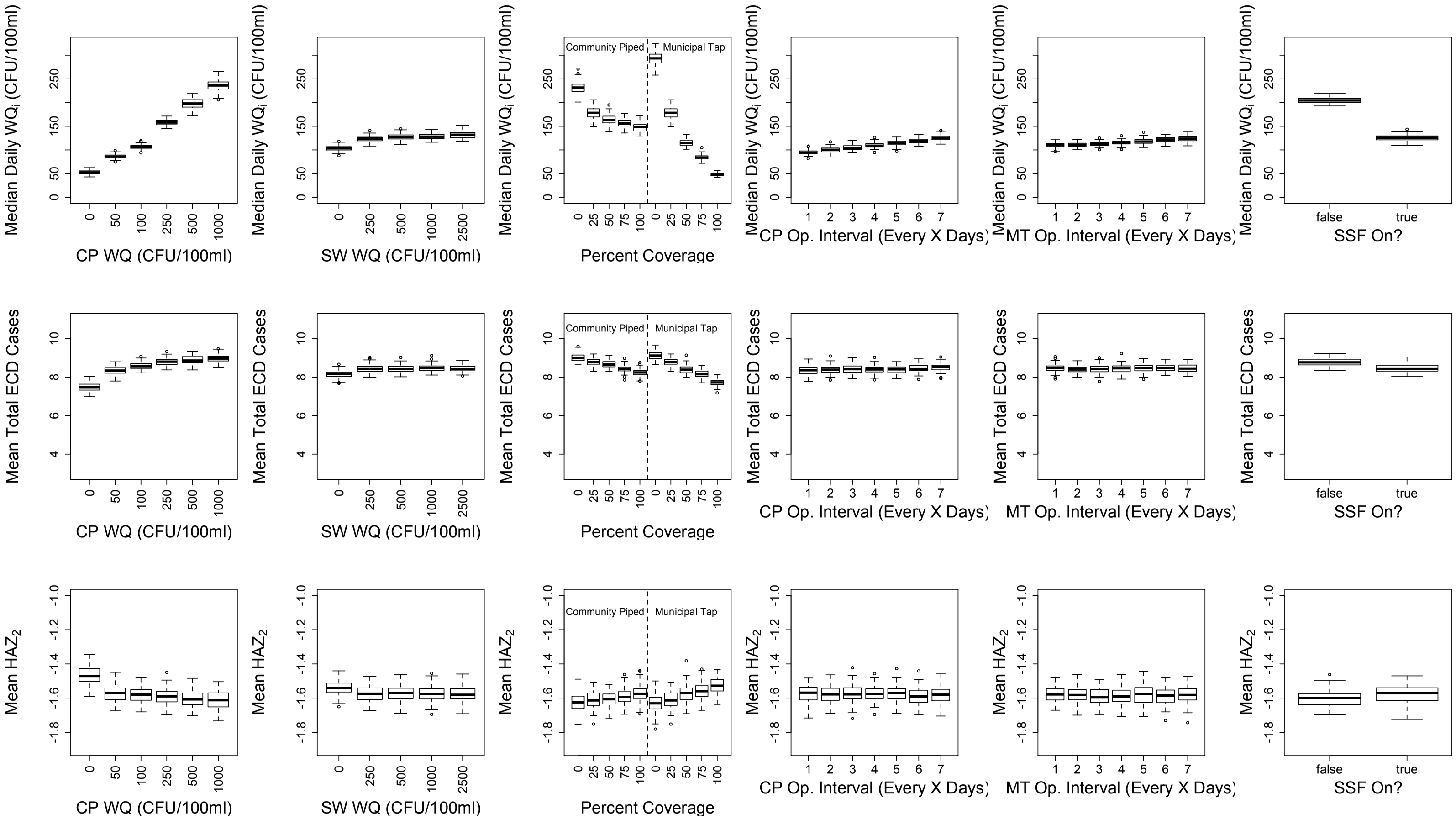

Figure A.13: *Sensitivity analysis for six additional important model parameters. Results summarized in terms of median daily WQ_i, mean total ECD cases, and mean HAZ_2. CP WQ and SW WQ refer to the source water quality of the community piped water system and surface water respectively. The non-linear x-axes are representative of field measurements. Percent coverage refers to two experiments that varied CP and MT water system reliance with the remaining houses depending on other water sources. CP and MT op. interval refer to the operational interval of those water sources. SSF refers to the operation of the community slow sand filter which is part of the CP water system. Results indicate median WQ_i variation in most cases, but this translated into large changes in ECD rates and HAZ_2 scores for only CP WQ and the percent coverage of MT and CP.*

APPENDIX B

Computer Code

```
extensions [array table]
breed [ households household]

breed [ children child ]


undirected-link-breed [housetokids housetokid]                    ;;directed link from
    child to HH


households-own [
 pri-water-source                    ;A households primary water source.  1 = River, 2 =
     Community Piped, 3 = Municipal Tap, 4 = Hose (CP system in Tshibvumo where pipes come from
     the river, but don't go through any kind of treatment)
 sec-water-source                    ;A households secondary water source.  1 = River, 2 =
     Community Piped, 3 = Municipal Tap, 4 = Hose (CP system in Tshibvumo where pipes come from
     the river, but don't go through any kind of treatment)
 daily-wq                            ;The main water household quality parameter that
     changes every day according to the water chain model.
 storage-container                   ;Storage container type.  1 = Wide necked, 2 = narrow
     neck
 days-keep-water                     ;Number of days keep water, used for biological
     regrowth
 hh-days-can-wait                    ;The maximum number of days a household can wait until
     they must get water
 today-source                        ;The source a household is using today, is usually
     equal to pri-water-source except when that source isn't working
 river-rand-number                   ;Random number used to determine which biological
```

```
     regrowth regime to use.
 pipe-rand-number                        ;Random number used to determine which biological
     regrowth regime to use.
 hand-wash-number                        ;Number used in hand-washing effectiveness calculation
 cf-education-level
 tap-min                                 ;Minimum number of days between water collection
 tap-max                                 ;Maximum number of days between water collection
 days-waiting                            ;Days waiting for water to start working again after
     checked for the first time
 has-filter
 jc_total                                ;Amount of total coliform bacteria associated with the
     sidewalls of the storage containers
 cup_total                               ;Amount of total coliform bacteria associated with the
     water transfer devices used for wide mounth containers
 clean-min                               ;Minimum number of days between container cleanings
 clean-max                               ;Maximum number of days between container cleanings
 boil-max                                ;Maximum number of days between water boilings
 boil-min                                ;Minimum number of days between water boilings
 hw-max                                  ;Maximum number of times wash hands per day
 hw-min                                  ;Minimum number of times wash hands per day
 bhw_total                               ;Total coliform bacteria associated with hands before
     washing hands.
 filrannum                               ;Random number that determines what linear filter
     deterioriation track a household will take
 days-have-filter
]

watersources-own [
  source-kind                            ;Just used for display purposes.

]



children-own[
 sex                                     ;1 = male, 2 = female
 age                                     ;0 to 730 days
 ecd                                     ;Does have ecd or not
 ecd-cases                               ;Total number of ecd cases per child
 height                                  ;Height

 stuntdays                               ;Days with stunted growth
 growthdelta                              ;Daily incremental increase in height when have acute
     case of ECD
 pastgot                                 ;Did a kid have a prolonged case of ECD during their
     first year
 have-had-diarrhea
 doublecases                          ;Total cases of prolonged ECD
 vaccinated                              ;Vaccinated against rotavirus?
 growth-factor

]
```

```
globals [xmin xmax ymin ymax                ;Parameters for Interface
  height-array                              ;Standard curve array for boys
  feight-array                              ;Standard curve array for girls
  bheight730                                ;Array of boys heights at age 2
  gheight730                                ;Array of girls heights at age 2
  totalpersistent
  pipewq                                    ;Array of piped WQ measurements
  mtwq                                      ;Array of MT WQ measurements
  surfwq                                    ;Array of surface WQ measurements
  all-ecd-cases                             ;Total number of ECD cases
  ecdprob                                   ;Array of probabilities of still having ECD for a given
       number of days
  grand-total-days-with-ecd                 ;Total of all kid's days-with-ecd
  totalstuntdays                            ;Total number of stunted growth days
  nostuntdays                               ;Total number of days without stunting
  haz0 haz60 haz120 haz180 haz240 haz300 haz360 haz420 haz480 haz540 haz600 haz660 haz730   ;Array
       of HAZs at each age in days
  haz30 haz90 haz150 haz210 haz270 haz330 haz390 haz450 haz510 haz570 haz630 haz690
  last-day-pipe-work                        ;The 'tick' when the piped system last worked
  last-day-MT-work                          ;The 'tick' when the MT system last worked
  last-day-hose-work                        ;The 'tick' when the hose system last worked
  BSD GSD                                   ;Arrays of the standard deviations of both boys and
      girls heights
  pre-pro-haz
  rannum1000 rannum100 rannum10 rannum1     ;Variables for different col-ecd scenarios for the
      ranges of  coliform levels
  mean-daily-wq-list                        ;Daily mean water qualities.
  all-double-cases                       ;Sums up all prolonged and acute ECD cases
  all-single-cases
  malheight-array malfeight-array
  collection-times                          ;Counts total number of times houses collect water
  water-usage-array                         ;Array of probabilities of a child drinking water on a
      given day
  days-keep-water-list                      ;List of days-keep-water
  boil-events                               ;Counter for number of times houses boil their water
  daily1000 daily100 daily10 daily1 daily0  ;Counters to show percent of houses with water quality
       of a given quality
  median-daily-wq-list                       ;Median daily WQ
  total-days-waiting                         ;Total days waiting
  haz-table
  haz-table-double
  ecdage-list
  ecdage-list-double
  broken
  grand-total-ecd-cases
  ]

to setup
  ca
  ifelse FIR = TRUE[
  set-current-directory "/h1/j/je/jem3w/netlogo-4.1.1/whil"][
```

```
set-current-directory "/Users/jem3w/Documents/limpopo/abm/"
import-drawing "map.tiff"  ]
set xmin 30.4336
set xmax 30.4630
set ymin -22.790
set ymax -22.7718
set-default-shape households "house"
set-default-shape watersources "circle"
set bheight730 []
set gheight730 []
set haz0 [] set haz60 [] set haz120 [] set haz180 []  set haz240 []  set haz300 []  set haz360
    []  set haz420 []  set haz480 []  set haz540 []  set haz600 []  set haz660 [] set haz730 []
set haz30 [] set haz90 [] set haz150 [] set haz210 [] set haz270 [] set haz330 [] set haz390 []
    set haz450 [] set haz510 [] set haz570 [] set haz630 [] set haz690 []
;set ecd-list []
set all-ecd-cases []
set grand-total-days-with-ecd []
set all-double-cases []
set all-single-cases []
set mean-daily-wq-list []
set median-daily-wq-list []
set pre-pro-haz []
set totalpersistent 0
set totalstuntdays 0
set nostuntdays 0
set days-keep-water-list [1 ]




set mtwq []
set pipewq []
set surfwq []

;Pipe, MT, and SURF water quality lists.  Each element of the list represents a field
    measurement.
set pipewq [440  585  420  460  0  0  540  120  1220  1160  40  40  80  680  0  0  640  200  180
    120  480  560  0  40]
set mtwq [300  0  380  195  20  35  0  180  0  0  0  0  0  40  0  280  200  300  0  0  80  60
    20  500  0  0  0  60  0  0]
set surfwq [880  680  1150  1330  1210  1120  2120  1260  2120  1220  160  3000  1240  1160
    1280  1020  20  300  715  500  930  860  640  990  480  870  120  140  820  1200  1565  1280
    200  305  100  160  200  4120  200  900  560  500  100  140  600  540  3020  3020  860
    740  720  600  240  120  200  380  1060  720  0  0  60  160  780  1020  640  420  700  580
    1300  1460  100  140]
;If performing water quality tests then take water quality values from Interface input
if pipe-wq-test = TRUE [set pipewq [] set pipewq fput pipe-quality-test pipewq]
if surf-wq-test = TRUE [set surfwq [] set surfwq fput surf-quality-test surfwq]
if mt-wq-test = TRUE [set mtwq [] set mtwq fput mt-quality-test mtwq]

;Based on digital reading of Figure 1 of Dr. Guerrant's 1986 paper: Prolonged and Recurring
    Diarrhea in Northeast of Brazil: Examination of Cases
```

```
  ;from a Community-Based Study.  Essentially a probabiliy of having diarrhea after some number of
       days


  ;SD from http://www.cdc.gov/growthcharts/who_charts.htm also Mei 2007
  set BSD array:from-list [1.90  1.95  2.01  2.05  2.09  2.12  2.15  2.18  2.21  2.25  2.29  2.34
       2.38  2.43  2.49  2.54  2.59  2.65  2.70  2.76  2.82  2.88  2.94  3.00  3.06 3.12 3.18 3.24
       3.3 3.36 3.42] ;3.12 and after are approximations
  set GSD array:from-list [1.86  1.95  2.03  2.10  2.16  2.22  2.26  2.31  2.37  2.41  2.47  2.52
       2.57  2.63  2.68  2.74  2.79  2.85  2.90  2.96  3.01  3.07  3.12  3.17  3.22 3.27 3.32 3.37
       3.42 3.47 3.52]


  make-height-array
  setup-households 0 0
  setup-hh-water-sources
  setup-containers
  setup-collect-freq
  setup-boil
  setup-hw
  setup-initial-children
  setup-haz
 ; do-plots



end

to go


 collect-water2
 treat-water
 kids-drink
 calculate-height4
 child-born
 child-old
 do-plots
 tick
 if ticks > totaldays [

    stop ]

end

to setup-initial-children
let j 1
while [ j <= 410 ]
[
ask household random 410
[
  hatch-children 1 [ set color green set size 1
```

```
    ;if random 100 < 77 [set vaccinated 1]   ;About 80% of the children have been vaccinated
         against rotavirus
    set ecd 0
    set ecd-cases 0
    set pastgot 0
     set doublecases 0
    ifelse (random 100 > 50) ; sex ratio of 1.02 from https://www.cia.gov/library/publications/the
         -world-factbook/geos/sf.html
    [set sex true]
    [set sex false]
    create-housetokid-with myself   ;creates link between households and children born there
    set age 0



        ;Sets initial height equal to CDC norms and standard deviations for newborns
        ifelse(sex = TRUE)
        [set height random-normal 48.14 1.9019] ;SD Using R and http://www.cdc.gov/growthcharts/
             who/boys_length_weight.htm
        [set height random-normal 47.72 1.8584] ;SD Using R and http://www.cdc.gov/growthcharts/
             who/girls_length_weight.htm
    girls_length_weight.htm

  ]
]

set j j + 1
]
end




to-report wq-report                   ;Reports mean of the median-daily-wq-list
  report mean median-daily-wq-list
end
to-report wq-report2                  ;Reports mean of the mean-daily-wq-list
  report mean mean-daily-wq-list
end
to-report keep-water-report           ;Reports how many days keep water on average
  report mean days-keep-water-list
end
to-report child-number                ;Total number of children
  report count children
end
to-report ave-height                  ;Average height of 2 year olds
  report mean bheight730
end
to-report ave-height2
  report mean gheight730
end
to-report girl-length                ;Number of girls and boys
```

```
  report length gheight730
end
to-report boy-length
  report length bheight730
end
to-report total-single                 ;Total Acute ECD cases
  report mean all-ecd-cases - mean all-double-cases
end
to-report total-double            ;Total prolonged ECD cases
  report mean all-double-cases
end
to-report ecd-all                      ;Mean ALL ECD cases
  report mean all-ecd-cases
end
to-report ecd-all2                      ;Median ALL ECD cases
  report median all-ecd-cases
end
to-report total-stunt-days             ;Calculates the percentage of stunting days
  report totalstuntdays / (totalstuntdays + nostuntdays) * 100
end
to-report percent-boil-days             ;Percent of days that folks boil their water
  report boil-events / (ticks * 410) * 100
end
to-report daily-1000                     ;Percent of households with the following water qualities
  report daily1000 / (daily1000 + daily100 + daily10 + daily1 + daily0) * 100
end
to-report daily-100
  report daily100 / (daily1000 + daily100 + daily10 + daily1 + daily0) * 100
end
to-report daily-10
  report daily10 / (daily1000 + daily100 + daily10 + daily1 + daily0) * 100
end
to-report daily-1
  report daily1 / (daily1000 + daily100 + daily10 + daily1 + daily0) * 100
end
to-report daily-0
  report daily0 / (daily1000 + daily100 + daily10 + daily1 + daily0) * 100
end
to-report totaldayswwaiting
  report total-days-waiting / collection-times
end

to collect-water2

;First decide which sources are working (pipe, MT and hose) Data from average of reported
    how_freq_sorce_work for each.
;That data is in terms of how many days per week each source works.  1 = everday, 7 = once a week
   if random-float 7 > 3.18 [set last-day-pipe-work ticks]
   if random-float 7 > 4.79 [set last-day-MT-work ticks]
   if random-float 7 > 2.3 [set last-day-hose-work ticks]
   if pipe-rel-test = TRUE [if random-float 7 > pipe-test [set last-day-pipe-work ticks]]     ;Can
       adjust the frequency of each source working by adjusting source-test inputs in Interface
```

```
if MT-rel-test = TRUE [if random-float 7 > MT-test [set last-day-MT-work ticks]]
if hose-rel-test = TRUE [if random-float 7 > hose-test [set last-day-hose-work ticks]]




ask households[
  set days-keep-water days-keep-water + 1 ;Increment days keep water for incubation experiment
      and cleaning







  let collect-freq (random (tap-max - tap-min) + tap-min)     ;Calculate collection frequency
      as a random number bewteen tap-min and tap-max, in terms of every 1, 2, 3 days...

  if collect-test = TRUE                                      ;If performing the water
      collection frequency test
  [set collect-freq collect-level                             ;Set collect-freq to the collect-
      level (which is input on the Interface)
    set last-day-pipe-work ticks                              ;Make each source work everyday
        so that you can study the collection frequency without the confounding
    set last-day-MT-work ticks                                ;question of deciding whether or
        not the source is working
    set last-day-hose-work ticks
  ]
  if remainder ticks collect-freq = 0 or days-waiting > 0 [;If today is a multiple of the
      collection-frequency or they are waiting for source to start working again then we'll
      look to collect today
    if today-source = 2 [                                     ;For piped water system
      ifelse (ticks - last-day-pipe-work = 0)      ;If the piped system is working today then
          collect water
      [ ;if days-waiting = 0 and ticks != 0 [print "***" print ticks print last-day-pipe-work
          print collect-freq ]
        set today-source pri-water-source                     ;Reset to primary water souce if
            had to go to secondary source during previous day.
        set days-waiting 0                                    ;Set days-waiting to zero
        set daily-wq item random length pipewq pipewq         ;Set daily-wq as random choice
            from water quality data
        set total-days-waiting days-keep-water + total-days-waiting    ;Add to the total days
            waiting
        set collection-times collection-times + 1                     ;Increment collection-
            times
        if (sand-filter-on = TRUE)                            ;If the sand-filter is ON
        [
           set daily-wq daily-wq * (random 10 + 1) / 100       ;Setting up Slow Sand Filter to
               have 1-2 log removal (90-99%)
        ]

        set days-keep-water 0                                  ;Set incubation days keep water
            variable to zero
```

```
    ]
    [
      ifelse hh-days-can-wait > days-waiting                  ;If the source isn't working
          today then check to see if a house has waited as long as it can this was taken from
           survey data
      [set days-waiting days-waiting + 1]                     ;If it can wait longer then
          increment days-waiting
      [set today-source sec-water-source]                     ;If not, then use secondary
          source on the next day
    ]
  ]
  if today-source = 3 [                                       ;For MT water system
    ifelse (ticks - last-day-MT-work = 0)        ;If the system is working today then collect
        water
    [
      set today-source pri-water-source                       ;Reset to primary water souce if
          had to go to secondary source.
      set days-waiting 0                                      ;Set days-waiting to zero
      set daily-wq item random length mtwq mtwq               ;Set daily-wq as a random choice
          from water quality data
      set collection-times collection-times + 1               ;Increment collection times
          variable
      set total-days-waiting days-keep-water + total-days-waiting
      set days-keep-water 0                                   ;Set incubation variable to zero
    ]
    [
      ifelse hh-days-can-wait > days-waiting                  ;If the source hasn't worked
          recently then see if a house has waited as long as it can
      [set days-waiting days-waiting + 1]                     ;If it can wait longer then
          increment days-waiting
      [set today-source sec-water-source]                     ;If not, then use secondary
          source on the next day
    ]
  ]
  if today-source = 4[                                        ;For Hose water system
    ifelse (ticks - last-day-hose-work = 0)       ;If the system is working today then collect
         water
    [
      set days-waiting 0
      set today-source pri-water-source                       ;Reset to primary water souce if
          had to go to secondary source.
      set daily-wq item random length pipewq pipewq           ;Set daily-wq according to the
          data
      set collection-times collection-times + 1
      set total-days-waiting days-keep-water + total-days-waiting
      set days-keep-water 0                                   ;Set incubation variable to zero
    ]
    [
      ifelse hh-days-can-wait > days-waiting                  ;If the source hasn't worked
          recently then see if a house has waited as long as it can
      [set days-waiting days-waiting + 1]                     ;If it can wait longer then
```

```
          increment days-waiting
        [set today-source sec-water-source ]                    ;If not, then use secondary
          source on the next day
      ]
    ]
    if today-source = 1 [                                       ;For River System - is always
        working
      set today-source pri-water-source                        ;Reset to primary water souce if
          had to go to secondary source.
      set days-waiting 0                                        ;Set days-waiting to zero
      set daily-wq item random length surfwq surfwq            ;Set daily-wq according to the data
      set collection-times collection-times + 1
      set total-days-waiting days-keep-water + total-days-waiting
      set days-keep-water 0                                     ;Set incubation variable to zero
    ]
  ]
  let volume random (20 - .5) + .5                              ;Calculating the volume of the
      water in storage containers.  Volumes were measured during HHB study and had a flat
      distribution from 0.5 to 20L

  let rannum (random-float (volume - .5) + .5) / .5             ;The ability of bacteria measured
      for the jc_total experiment to disattach itself and contaminate the
  ;water is unknown.  To model this phonemenom we take the typical volume of stored water and
      assume that the dilution factor is somewhere between 1 and
  ;Volume / 0.5 L where 0.5 L was the volume of the water used in the jc_total experiment.
  ;This is then used as a dilution factor in the code below.
  if rannum > 39 [print rannum]
  if(daily-wq < (jc_total / rannum)) [set daily-wq (jc_total / rannum)]  ;WQ cannot go below
      the biofilm layer amount => 108 = 9.65L / 0.1L

  if storage-container = 2 [set daily-wq daily-wq + (cup_total + bhw_total) / (volume / .5)]  ;
      If a household has an open style container then add in cup_total as the amount added by
      dipping in a cup
  ;No dilution factor is used in this case because the experiment closely mimicked the actual
      way folks will do it.




]



if coliform-growing = TRUE[
  ask households[


    ;Coliform incubation growth for River/Closed is located in position 3 in the following
        vectors under today-source = 1
    ;Coliform incubation growth for Pipe/Closed is located in positions 2,3 in the following
        vectors under today-source = 2 or 4
    ;Coliform incubation growth for River/Open is located in positions 0,1,2 in the following
```

```
        vectors under today-source = 1
    ;Coliform incubation growth for Pipe/Open is located in positions 0,1 in the following
        vectors under today-source = 2 or 4

    if (today-source = 1) ;River
    [

      if(days-keep-water = 1) [set daily-wq daily-wq * (item river-rand-number [0.7695  7.6905
           11.0753  7.7073])]  ;Numbers based on incubation survey
      if(days-keep-water = 2) [set daily-wq daily-wq * (item river-rand-number [1.6361  1.9938
           1.8913  3.1962])]
      if(days-keep-water = 3) [set daily-wq daily-wq * (item river-rand-number [0.6398  0.3126
           0.0020534  0.3881])]
      if(days-keep-water = 4) [set daily-wq daily-wq * (item river-rand-number [1.3877  2.2384
           148.2500  2.2143])]
      if(days-keep-water = 5) [set daily-wq daily-wq * (item river-rand-number [0.9933  0.3299
           1.7251  0.3629])]
      if(days-keep-water = 6) [set daily-wq daily-wq * (item river-rand-number [0.6763  3.3632
           0.9932  1.4730])]

    ]
    if (today-source = 2 or today-source = 4) ;Piped or Hose
    [

      if(days-keep-water = 1) [set daily-wq daily-wq * (item pipe-rand-number [47.2800  43.9091
            4.4211  23.7500])]  ;Numbers based on incubation survey
      if(days-keep-water = 2) [set daily-wq daily-wq * (item pipe-rand-number [0.1447  1.6687
          3.4881  1.7474])]
      if(days-keep-water = 3) [set daily-wq daily-wq * (item pipe-rand-number [5.2632  0.6203
          1.1058  0.3976])]
      if(days-keep-water = 4) [set daily-wq daily-wq * (item pipe-rand-number [1.4089  1.1740
          0.4167  2.3864])]
      if(days-keep-water = 5) [set daily-wq daily-wq * (item pipe-rand-number [1.0174  0.2828
          0.8000  0.7937])]
      if(days-keep-water = 6) [set daily-wq daily-wq * (item pipe-rand-number [1.1752  1.2560
          1.3426  0.9400])]
    ]




    ;set color scale-color green daily-wq 0 2000
    ;set color scale-color green days-keep-water 0 6
    ;ifelse days-keep-water > 6 [set color 15][set color 108]
    ;ifelse daily-wq > 1000 [set color 15][set color 108]
  ]
]

ask households[


  let clean-freq (random (clean-max - clean-min) + clean-min) ;Calculate cleaning frequency to
```

```
        be somewhere between clean min and clean max values

    if clean-test = TRUE          ;If in clean-test mode set clean-freq to value on Interface
      [set clean-freq clean-level]

    if(remainder ticks clean-freq = 0)
      [
        let randnum random-float (.80 - .73) + .73          ;0.80 is a 20% decrease seen in
            biofilm follow-up experiment whereby we scraped the sides of the containers and got a
             median 20% resuspension of bacteria.  The 0.73 is the percentage difference between
            Good and OK bucket washers in HHB study
        set daily-wq daily-wq * randnum
      ]
  ]



end







to treat-water

  ask households
  [

    let boil-freq (random (boil-max - boil-min) + boil-min)     ;boil-freq is a number that
        represents how frequently to boil, 1 would be everday, 2 every other day, 7 once a week
        etc...

    if boil-test = TRUE [set boil-freq boil-level]              ;If in boil testing mode then set
         boil-freq equal to that on the Interface
    set boil-freq boil-freq; * boil-education-level
    let cf-use-today FALSE

    if has-filter = 1
    [
     ; set daily-wq daily-wq * .01                              ;If a household has a filter
         then assume that they don't boil their water and there is a 99% reduction in bacteria

      if random-float 100 < abs (LOG (1 - break-rate / 100) 730) [set has-filter 0 set broken
          broken + 1]
      if ticks = break-date [set has-filter 0 set broken broken + 1]
      let ticks2 0
      ifelse constant = TRUE
      [set ticks2 0]
      [set ticks2 ticks]
```

```
ifelse effect = TRUE
  [
    set daily-wq daily-wq * effectiveness
  ]
  [
    ifelse SA = TRUE
    [


        if ticks2 >= 0 and ticks2 <= 365 and random 100 < cf-usage
        [

          set cf-use-today TRUE
          if filrannum = 0 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.006670276 +
               4.025715384))]
          if filrannum = 1 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.005830596 +
               3.556302501))]
          if filrannum = 2 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.004302276 +
               3.877946952))]
          if filrannum = 3 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * 0.002408141 +
               3.579326204))]
          if filrannum = 4 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.002920785 +
               3.496583734))]
          if filrannum = 5 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.001556412 +
               3.073240317))]
          if filrannum = 6 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.000659039 +
               2.416640507))]
          if filrannum = 7 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.003028795 +
               1.939519253))]
          if filrannum = 8 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * 0.002205166 +
               2.62324929))]
          if filrannum = 9 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.007257286 +
               2.465382851))]
          if filrannum = 10 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.00190856 +
               1.98811284))]
          if filrannum = 11 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.005870949 +
               1.477349991))]
          if filrannum = 12 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.006008339 +
               3.338456494))]
          if filrannum = 13 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.002775483 +
               2.899541923))]
          if filrannum = 14 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.001252466 +
               2.40654018))]
          if filrannum = 15 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.005611106 +
               3.155639634))]
          if filrannum = 16 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.002885321 +
               2.755874856))]
          if filrannum = 17 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.006589247 +
               3.550228353))]
          if filrannum = 18 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.005826309 +
               3.122215878))]
          if filrannum = 19 [set daily-wq daily-wq * 10 ^  ( - (ticks2 * -0.004270591 +
```

```
      2.117271296))]
  if filrannum = 20 [set daily-wq daily-wq * 10 ^  (- (ticks2 * 0.00085923 +
      2.62838893))]
  if filrannum = 21 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.006788884 +
      3.042236765))]
  if filrannum = 22 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.003020307 +
      3.327358934))]
  if filrannum = 23 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.005111595 +
      2.937016107))]
  if filrannum = 24 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.001438865 +
      2.667452953))]
  if filrannum = 25 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.004212457 +
      1.113943352))]
  if filrannum = 26 [set daily-wq daily-wq * 10 ^  (- (ticks2 * 0.000419865 +
      2.867938651))]
  if filrannum = 27 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.004259082 +
      2.411619706))]
  if filrannum = 28 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.004623036 +
      3.350248018))]
  if filrannum = 29 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.004813594 +
      3.903089987))]
  if filrannum = 30 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.000362068 +
      0.698970004))]
  if filrannum = 31 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.006941793 +
      2.983626287))]
  if filrannum = 32 [set daily-wq daily-wq * 10 ^  (- (ticks2 * 0.000135645 +
      3.025305865))]
  if filrannum = 33 [set daily-wq daily-wq * 10 ^  (- (ticks2 * 0.003439103 + 2))]


]
if ticks2 > 365 and ticks2 <= 1095 and random 100 < cf-usage
[
  set cf-use-today TRUE

  if filrannum = 0 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.00532072 +
      3.533127444))]
  if filrannum = 1 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.00484736 +
      3.197421108))]
  if filrannum = 2 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.003238484 +
      3.489662744))]
  if filrannum = 3 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.001890193 +
      5.148218289))]
  if filrannum = 4 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.000707785 +
      2.688838788))]
  if filrannum = 5 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.002590313 +
      3.450614356))]
  if filrannum = 6 [set daily-wq daily-wq * 10 ^  (- (ticks2 * 0.00061272 +
      1.952448326))]
  if filrannum = 7 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.000921538 +
      1.170370477))]
  if filrannum = 8 [set daily-wq daily-wq * 10 ^  (- (ticks2 * -0.000129325 +
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    3.475338485))]
if filrannum = 9 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.002071592 +
    0.572604641))]
if filrannum = 10 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.004508888 +
    2.937232793))]
if filrannum = 11 [set daily-wq daily-wq * 10 ^ (- (ticks2 * 0.000695112 +
    -0.919261984))]
if filrannum = 12 [set daily-wq daily-wq * 10 ^ (- (ticks2 * 0.001150044 +
    0.725646383))]
if filrannum = 13 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.002268672 +
    2.714555866))]
if filrannum = 14 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.001431639 +
    2.471938276))]
if filrannum = 15 [set daily-wq daily-wq * 10 ^ (- (ticks2 * 0.002568549 +
    0.170065494))]
if filrannum = 16 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.00162379 +
    2.295416071))]
if filrannum = 17 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.002531632 +
    2.069198777))]
if filrannum = 18 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.00261323 +
    1.949441972))]
if filrannum = 19 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.000483276 +
    0.734901482))]
if filrannum = 20 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.00123372 +
    3.392315737))]
if filrannum = 21 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.001744233 +
    1.200939389))]
if filrannum = 22 [set daily-wq daily-wq * 10 ^ (- (ticks2 * 0.000671232 +
    1.979947251))]
if filrannum = 23 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.001022801 +
    1.444606627))]
if filrannum = 24 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.001138927 +
    2.557975412))]
if filrannum = 25 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.00011201 +
    -0.382720071))]
if filrannum = 26 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.002305709 +
    3.86277302))]
if filrannum = 27 [set daily-wq daily-wq * 10 ^ (- (ticks2 * 0.000195816 +
    0.78558195))]
if filrannum = 28 [set daily-wq daily-wq * 10 ^ (- (ticks2 * 0.000181124 +
    1.596729609))]
if filrannum = 29 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.001903897 +
    2.841050617))]
if filrannum = 30 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.000939514 +
    0.909737541))]
if filrannum = 31 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.003296797 +
    1.65320293))]
if filrannum = 32 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.001175884 +
    3.504013918))]
if filrannum = 33 [set daily-wq daily-wq * 10 ^ (- (ticks2 * -0.004240837 +
    4.803177866))]
```

```
    ]

]

[;If Guatemala Data

  if ticks2 <= 210 and random 100 < cf-usage[

    set cf-use-today TRUE

    if filrannum = 1 [ set daily-wq daily-wq * (1 - (ticks2 * -7.21501E-05 + 1) )]
    if filrannum = 2 [ set daily-wq daily-wq * (1 - (ticks2 * -0.002142857 + 1) )]
    if filrannum = 3 [ set daily-wq daily-wq * (1 - (ticks2 * -4.52381E-05 + 1) )]
    if filrannum = 4 [ set daily-wq daily-wq * (1 - (ticks2 * -6.52316E-05 + 1) )]
    if filrannum = 5 [ set daily-wq daily-wq * (1 - (ticks2 * 0 + 1) )]
    if filrannum = 6 [ set daily-wq daily-wq * (1 - (ticks2 * -1.66667E-05 + 1) )]
    if filrannum = 7 [ set daily-wq daily-wq * (1 - (ticks2 * -7.23044E-06 + 1) )]
    if filrannum = 8 [ set daily-wq daily-wq * (1 - (ticks2 * 4.7619E-06 + 0.999) )]
    if filrannum = 9 [ set daily-wq daily-wq * (1 - (ticks2 * 0 + 1) )]
    if filrannum = 10 [ set daily-wq daily-wq * (1 - (ticks2 * 0.021904762 + 1) )]
    if filrannum = 11 [ set daily-wq daily-wq * (1 - (ticks2 * 0.221245421 + 1) )]
    if filrannum = 12 [ set daily-wq daily-wq * (1 - (ticks2 * 0 + 1) )]
    if filrannum = 13 [ set daily-wq daily-wq * (1 - (ticks2 * 0.004527829 + 1) )]
    if filrannum = 14 [ set daily-wq daily-wq * (1 - (ticks2 * 0 + 1) )]
    if filrannum = 15 [ set daily-wq daily-wq * (1 - (ticks2 * -3.6295E-05 + 1) )]
    if filrannum = 16 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000310559 + 1) )]
    if filrannum = 17 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000125865 + 1) )]
    if filrannum = 18 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000197619 + 1) )]
    if filrannum = 19 [ set daily-wq daily-wq * (1 - (ticks2 * -3.4632E-05 + 1) )]
    if filrannum = 0 [ set daily-wq daily-wq * (1 - (ticks2 * -3.30688E-05 + 1) )]

  ]
  if ticks2 > 210 and random 100 < cf-usage[


    set cf-use-today TRUE
    if filrannum = 1 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000754348 +
         1.143261587) )]
    if filrannum = 2 [ set daily-wq daily-wq * (1 - (ticks2 * 0.002563667 +
         0.011629881) )]
    if filrannum = 3 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000696485 +
         1.136761801) )]
    if filrannum = 4 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000442619 +
         1.079251294) )]
    if filrannum = 5 [ set daily-wq daily-wq * (1 - (ticks2 * -0.001228879 +
         1.258064516) )]
    if filrannum = 6 [ set daily-wq daily-wq * (1 - (ticks2 * -7.21412E-05 +
         1.011649661) )]
    if filrannum = 7 [ set daily-wq daily-wq * (1 - (ticks2 * 9.79608E-06 +
         0.996424432) )]
    if filrannum = 8 [ set daily-wq daily-wq * (1 - (ticks2 * 0.000679117 +
         0.857385399) )]
```

```
          if filrannum = 9 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000384396 +
               1.080723079)) ]
          if filrannum = 10 [ set daily-wq daily-wq * (1 - (ticks2 * -0.023678551 +
               10.57249576) )]
          if filrannum = 11 [ set daily-wq daily-wq * (1 - (ticks2 * -0.29363627 +
               109.1251551) )]
          if filrannum = 12 [ set daily-wq daily-wq * (1 - (ticks2 * 0 + 1) )]
          if filrannum = 13 [ set daily-wq daily-wq * (1 - (ticks2 * 0.000293503 +
               0.889208543) )]
          if filrannum = 14 [ set daily-wq daily-wq * (1 - (ticks2 * -0.000195503 +
               1.041055718) )]
          if filrannum = 15 [ set daily-wq daily-wq * (1 - (ticks2 * 4.91739E-05 +
               0.982051534) )]
          if filrannum = 16 [ set daily-wq daily-wq * (1 - (ticks2 * 0.000398813 +
               0.851031857) )]
          if filrannum = 17 [ set daily-wq daily-wq * (1 - (ticks2 * 0.000170527 +
               0.937757567) )]
          if filrannum = 18 [ set daily-wq daily-wq * (1 - (ticks2 * -0.001188351 +
               1.208053763)) ]
          if filrannum = 19 [ set daily-wq daily-wq * (1 - (ticks2 * -0.00033134 +
               1.062308628) )]
          if filrannum = 0 [ set daily-wq daily-wq * (1 - (ticks2 * -2.38313E-05 +
               0.998060131) )]

        ]
        if daily-wq < 0 [set daily-wq 0]



      ]



    ]
  ]




  if cf-use-today = FALSE [;If not filter then default to boiling
    if remainder ticks boil-freq = 0                    ;From Clasen Papers (Guatemala
         2010, India 2008, Vietnam 2007)  Used normal dist calc to get SDs from CIs (http://
         onlinestatbook.com/chapter8/mean.html)
    [ set boil-events boil-events + 1                   ;Counts number of boil events
      let boil-effectiveness random-normal 0.01431 0.001109
      if (boil-effectiveness < 0) [set boil-effectiveness 0]  ;Just in case get a negative
           number (very rare)
      set daily-wq boil-effectiveness * daily-wq   ;Mean, SD, N  Guat: .88 .075 206 :: India:
           2.1 .025 1088 :: Viet: 1.52 0.046 245 Took weighted average by N for means and SDs to
            get these values
    ]
  ]
]
```

```
end

to kids-drink



                  ;Uses the two most recent papers on coliform-ecd correlations.  Brown 2008 and
                      Jensen
    set rannum1000 random-float (3.29 - 1.08) + 1.08
    set rannum100 random-float (3.71 - 0.94) + 0.94
    set rannum10 random-float (3 - 0.87) + 0.87
    set rannum1 random-float (2 - 0.75) + 0.75

    set rannum1000 rannum1000 * col-ecd-factor
    set rannum100 rannum100 * col-ecd-factor
    set rannum10 rannum10 * col-ecd-factor
    set rannum1 rannum1 * col-ecd-factor


  let daily-wq-list2 []
  ask households [

    if(daily-wq > random-normal 4000 250)[set daily-wq random-normal 4000 250]  ;4000 was the
        highest recorded during Dec-July 2010-11 household testing, 250 is arbitrary


    ;if rannum2 < 1 [set daily-wq-list fput daily-wq daily-wq-list]
    set daily-wq-list2 fput daily-wq daily-wq-list2                          ;Take each
        household's daily WQ value and put it into daily-wq-list2


    let hw-freq (random (hw-max - hw-min) + hw-min) / 32  ;hw-freq is a number between 0 and 1
        that signifies the percent of 32 that people wash their hands see below for meaning of 32
    if hw-test = TRUE [set hw-freq hw-level / 32]  ;If in HW testing mode then set all hw-freq to
        a hw-level input on Interface

    set hand-wash-number 100 * ( ((hw-freq) * abs(random-normal .43 .0695))); + 100;From Curtis
        2000 paper (Domestic hygiene and diarrhoea  pinpointing the problem), washing at all
        critical times would mean 32 total times per day
                                                          ;.31  .43                  ;So, taking
                                                              linear approximation.  Also, using
                                                             Aiello 2008, hand-washing decreases
                                                             diarrheal diseases by 31% (95% CI,
                                                             19-42%). Calculated 6.95 using NORMINV
                                                              in


    ;set color scale-color orange hw-freq 0 1
    ;set color scale-color red daily-wq 10 0
```

```
let increase-risk-number 0.518;0.565;0.518;0.542

if (daily-wq >= 1000)                ;Worst case senario
  [ ask housetokid-neighbors [

    let rannum random-float 100 ;(item 0 [hand-wash-number] of housetokid-neighbors) ;
        Calculating a random number between 0 and something less than or equal to 100
        depending on the hand-washing behavior of the households.  This is used to slighly
        increase the probability that someone might get diarrhea if they drink poor water.
    if pastgot = 1 [set rannum rannum * increase-risk-number] ; Ave of 15.5%/29.9% and
        1.91/3.12 = 0.565 is from Moore 2010 paper - kids who get Prolonged diarrhea before
        age 1 are twice as likely to get persistent later in life
    if (rannum <= rannum1000) [ifelse ecd = 1 [set ecd 2][set ecd 1 set stuntdays 0]] ;Based
        on Brown 2008 Escherichia coli in household drinking water and diarrheal disease risk:
         evidence from Cambodia
    ;if (age < bf-age) [set ecd 0]
    set daily1000 daily1000 + 1    ;Incrementing incidences of daily-wq of this quality
  ]
  ]

if (daily-wq >= 100) and (daily-wq < 1000)    ;;extreme risk population
  [ ask housetokid-neighbors [

    let rannum random-float 100;(item 0 [hand-wash-number] of housetokid-neighbors)
    if pastgot = 1 [set rannum rannum * increase-risk-number] ; Ave of 15.5%/29.9% and
        1.91/3.12 = 0.565 is from Moore 2010 paper - kids who get Prolonged diarrhea before
        age 1 are twice as likely to get persistent later in life
    if (rannum <= rannum100) [ifelse ecd = 1 [set ecd 2][set ecd 1 set stuntdays 0]] ;Based on
         Brown 2008 Escherichia coli in household drinking water and diarrheal disease risk:
        evidence from Cambodia
    ;if (age < bf-age) [set ecd 0]
    set daily100 daily100 + 1     ;Incrementing incidences of daily-wq of this quality
  ]
  ]


  if (daily-wq >= 10) and (daily-wq < 100)  ;;high risk population
  [ask housetokid-neighbors [

      let rannum random-float 100;(item 0 [hand-wash-number] of housetokid-neighbors)
      if pastgot = 1 [set rannum rannum * increase-risk-number] ; Ave of 15.5%/29.9% and
          1.91/3.12 = 0.565 is from Moore 2010 paper - kids who get Prolonged diarrhea before
          age 1 are twice as likely to get persistent later in life
      if (rannum <= rannum10)[ifelse ecd = 1 [set ecd 2][set ecd 1 set stuntdays 0]]  ;Based
          on Brown 2008 Escherichia coli in household drinking water and diarrheal disease
          risk: evidence from Cambodia
     ; if (age < bf-age) [set ecd 0]
      set daily10 daily10 + 1    ;Incrementing incidences of daily-wq of this quality
    ]
  ]
```

```
    if (daily-wq < 10 and daily-wq >= 1)    ;;low risk population
    [ask housetokid-neighbors [

      let rannum random-float 100;(item 0 [hand-wash-number] of housetokid-neighbors)
      if pastgot = 1 [set rannum rannum * increase-risk-number] ; Ave of 15.5%/29.9% and
          1.91/3.12 = 0.565 is from Moore 2010 paper - kids who get Prolonged diarrhea before
          age 1 are twice as likely to get persistent later in life
      if (rannum <= rannum1)[ifelse ecd = 1 [set ecd 2][set ecd 1 set stuntdays 0]]   ;Based on
          Brown 2008 Escherichia coli in household drinking water and diarrheal disease risk:
          evidence from Cambodia
      ;if (age < bf-age) [set ecd 0]
      set daily1 daily1 + 1        ;Incrementing incidences of daily-wq of this quality
    ]
    ]

    if (daily-wq < 1) [ set daily0 daily0 + 1]    ;Incrementing incidences of daily-wq of this
        quality


]
ask children[

  if((stuntdays = 0 and ecd = 1) or ecd = 2)
    [

          if (random-float 100 >= array:item water-usage-array age)  [   ;Decide whether or
              not kids are drinking water based on MAL-ED data about child drinking habits
        if (ecd = 1 and stuntdays = 0)[set ecd 0]
        if (ecd = 2)[set ecd 1]

      ]
      if (random-float 100 < 44.1)[             ;Assume that all kids are vaccinated and there
          is a 44.1% reduction in ECD from the
        if (ecd = 1 and stuntdays = 0)[set ecd 0]
        if (ecd = 2)[set ecd 1]                 ;Rota Virus vaccine (Madhi 2010, Table 3 for
            South Africa)
      ]

        ;and vaccinated = 1

      if (random-float 100 < item 0 [hand-wash-number] of housetokid-neighbors) [  ;Reduces ECD
          for kids whose households washing their hands a lot
        if (ecd = 1  and stuntdays = 0)[set ecd 0]
        if (ecd = 2)[set ecd 1]

      ]
        ;if (random 100 < increase-risk-number) [set ecd ]

    ]
]
```

```
  ;]

;Put mean and median daily WQ values into their respective lists.
set mean-daily-wq-list fput mean daily-wq-list2 mean-daily-wq-list
set median-daily-wq-list fput median daily-wq-list2 median-daily-wq-list


end

to calculate-height4

  ask children[

     ;This routine is under development to incorporate MAL-ED data
     if((ecd = 1 and stuntdays = 0) or ecd = 2)[  ;If got ECD this time




       if age <= 365 [set pastgot 1]
       set ecd-cases ecd-cases + 1
       set have-had-diarrhea 1
       set grand-total-ecd-cases grand-total-ecd-cases + 1
       ifelse ecd = 1
       [
         let $match-list sort-by [abs(?1 - age) < abs(?2 - age)] ecdage-list
         set growth-factor (- (table:get haz-table first $match-list) / 240);stuntlength);]




       ]
       [
         let $match-list sort-by [abs(?1 - age) < abs(?2 - age)] ecdage-list-double
         set growth-factor (- (table:get haz-table-double first $match-list) / 240);stuntlength);]

         set doublecases doublecases + 1
         set ecd 1
         set stuntdays 0
            ]

         ]


     ifelse(ecd = 1)              ;If ECD
     [

      ifelse(sex = TRUE)     ;Boys and girls grow differently \
         [set growthdelta (((array:item height-array (age + 1)) - (array:item BSD floor ((age + 1)
              / 30)) * (growth-factor - (height - array:item height-array age) / (array:item BSD
             floor (age / 30))  ) - height))]  ;Numbers based on Moore and Mei papers
         [set growthdelta (((array:item feight-array (age + 1)) - (array:item GSD floor ((age + 1)
```

```
              / 30)) * (growth-factor - (height - array:item feight-array age) / (array:item GSD
             floor (age / 30))  ) - height))]  ;0.31 is HAZ reduction for Acute Cases in that
             paper

        set height height + growthdelta               ;Set height
        set stuntdays stuntdays + 1                   ;Count the number of stunted growth days from
             now for 180 days
        set totalstuntdays totalstuntdays + 1;stuntdays
        if (stuntdays > stuntlength) [set ecd 0  set stuntdays 0]
            ]
      [ ;If healthy




           ifelse(sex = TRUE)        ;Boys and girls growing at different rates.
           [set height (height + (array:item height-array (age + 1) - array:item height-array age))
                ]
           [set height (height + (array:item feight-array (age + 1) - array:item feight-array age))
                ]


           set nostuntdays nostuntdays + 1





      ]
   ]


end






to child-born

   if random-float 100 < 0 ;6 is the number that seems to give good birth rates similar to that
        which we are seeing in T&T
   [
     ask household random 410
     [       hatch-children 1[ set color yellow set size 1

         set ecd 0
         set age 0
         set ecd-cases 0
                set pastgot 0

         set doublecases 0
```

```
        ifelse (random 100 > 50)     ;51 is the approximate sex ratio in South Africa
        [set sex true]
        [set sex false]

        create-housetokid-with myself
        ifelse(sex = TRUE)
        [set height random-normal 48.14 1.9019] ;SD Using R and http://www.cdc.gov/growthcharts/
            who/boys_length_weight.htm
        [set height random-normal 47.72 1.8584] ;SD Using R and http://www.cdc.gov/growthcharts/
            who/girls_length_weight.htm


      ]
    ]
  ]


end

to child-old

  ask children
  [
   set age age + 1

   if (age > 730)
   [
     ;Save boy and girls heights
     ifelse(sex = TRUE)
     [set bheight730 fput height bheight730]
     [set gheight730 fput height gheight730]
     set all-ecd-cases fput ecd-cases all-ecd-cases
                                                                             ;Put number of cases of ECD into all-
         ecd-cases vector
     set all-double-cases fput doublecases all-double-cases
     die
   ]

  ;Save HAZ scores every 60 days for all kids.  Don't save scores every day because of memory
      problems.
   ifelse(sex = TRUE)[



     if(age = 1)[set haz0 fput ((height - array:item height-array age) / array:item BSD 0) haz0 ]

     if (age = 30)[set haz30 fput ((height - array:item height-array age) / array:item BSD 1)
         haz30]
     if (age = 90)[set haz90 fput ((height - array:item height-array age) / array:item BSD 3)
         haz90]
     if (age = 150)[set haz150 fput ((height - array:item height-array age) / array:item BSD 5)
         haz150]
```

```
if (age = 210)[set haz210 fput ((height - array:item height-array age) / array:item BSD 7)
    haz210]
if (age = 270)[set haz270 fput ((height - array:item height-array age) / array:item BSD 9)
    haz270]
if (age = 330)[set haz330 fput ((height - array:item height-array age) / array:item BSD 11)
    haz330]
if (age = 390)[set haz390 fput ((height - array:item height-array age) / array:item BSD 13)
    haz390]
if (age = 450)[set haz450 fput ((height - array:item height-array age) / array:item BSD 15)
    haz450]
if (age = 510)[set haz510 fput ((height - array:item height-array age) / array:item BSD 17)
    haz510]
if (age = 570)[set haz570 fput ((height - array:item height-array age) / array:item BSD 19)
    haz570]
if (age = 630)[set haz630 fput ((height - array:item height-array age) / array:item BSD 21)
    haz630]
if (age = 690)[set haz690 fput ((height - array:item height-array age) / array:item BSD 23)
    haz690]
if (age = 60)[set haz60 fput ((height - array:item height-array age) / array:item BSD 2)
    haz60]
if (age = 120)[set haz120 fput ((height - array:item height-array age) / array:item BSD 4)
    haz120]
if (age = 180)[set haz180 fput ((height - array:item height-array age) / array:item BSD 6)
    haz180]
if (age = 240)[set haz240 fput ((height - array:item height-array age) / array:item BSD 8)
    haz240]
if (age = 300)[set haz300 fput ((height - array:item height-array age) / array:item BSD 10)
    haz300]
if (age = 360)[set haz360 fput ((height - array:item height-array age) / array:item BSD 12)
    haz360]
if (age = 420)[set haz420 fput ((height - array:item height-array age) / array:item BSD 14)
    haz420]
if (age = 480)[set haz480 fput ((height - array:item height-array age) / array:item BSD 16)
    haz480]
if (age = 540)[set haz540 fput ((height - array:item height-array age) / array:item BSD 18)
    haz540]
if (age = 600)[set haz600 fput ((height - array:item height-array age) / array:item BSD 20)
    haz600]
if (age = 660)[set haz660 fput ((height - array:item height-array age) / array:item BSD 22)
    haz660]
if (age = 730)[set haz730 fput ((height - array:item height-array age) / array:item BSD 24)
    haz730]
]
[

if (age = 30)[set haz30 fput ((height - array:item feight-array age) / array:item GSD 1)
    haz30]
if (age = 90)[set haz90 fput ((height - array:item feight-array age) / array:item GSD 3)
    haz90]
if (age = 150)[set haz150 fput ((height - array:item feight-array age) / array:item GSD 5)
    haz150]
if (age = 210)[set haz210 fput ((height - array:item feight-array age) / array:item GSD 7)
```

```
      haz210]
    if (age = 270)[set haz270 fput ((height - array:item feight-array age) / array:item GSD 9)
      haz270]
    if (age = 330)[set haz330 fput ((height - array:item feight-array age) / array:item GSD 11)
      haz330]
    if (age = 390)[set haz390 fput ((height - array:item feight-array age) / array:item GSD 13)
      haz390]
    if (age = 450)[set haz450 fput ((height - array:item feight-array age) / array:item GSD 15)
      haz450]
    if (age = 510)[set haz510 fput ((height - array:item feight-array age) / array:item GSD 17)
      haz510]
    if (age = 570)[set haz570 fput ((height - array:item feight-array age) / array:item GSD 19)
      haz570]
    if (age = 630)[set haz630 fput ((height - array:item feight-array age) / array:item GSD 21)
      haz630]
    if (age = 690)[set haz690 fput ((height - array:item feight-array age) / array:item GSD 23)
      haz690]


    if (age = 1) [set haz0 fput ((height - array:item feight-array age) / array:item GSD 0) haz0
      ]
    if (age = 60)[set haz60 fput ((height - array:item feight-array age) / array:item GSD 2)
      haz60]
    if (age = 120)[set haz120 fput ((height - array:item feight-array age) / array:item GSD 4)
      haz120]
    if (age = 180)[set haz180 fput ((height - array:item feight-array age) / array:item GSD 6)
      haz180]
    if (age = 240)[set haz240 fput ((height - array:item feight-array age) / array:item GSD 8)
      haz240]
    if (age = 300)[set haz300 fput ((height - array:item feight-array age) / array:item GSD 10)
      haz300]
    if (age = 360)[set haz360 fput ((height - array:item feight-array age) / array:item GSD 12)
      haz360]
    if (age = 420)[set haz420 fput ((height - array:item feight-array age) / array:item GSD 14)
      haz420]
    if (age = 480)[set haz480 fput ((height - array:item feight-array age) / array:item GSD 16)
      haz480]
    if (age = 540)[set haz540 fput ((height - array:item feight-array age) / array:item GSD 18)
      haz540]
    if (age = 600)[set haz600 fput ((height - array:item feight-array age) / array:item GSD 20)
      haz600]
    if (age = 660)[set haz660 fput ((height - array:item feight-array age) / array:item GSD 22)
      haz660]
    if (age = 730)[set haz730 fput ((height - array:item feight-array age) / array:item GSD 24)
      haz730]

    ]
  ]


end
```

```
to setup-watersources
 ;This routine just places some of the water sources on the map.  It does not really do anything
     important.
  let i 0
  let j 1
  let k 2
  let ii 0
  let wat-list [ ]
  file-open "water_locations.txt"                                        ;; open txt file containing
      lat/long decimal format coordinates for all households
  while [not file-at-end?]
  [set wat-list lput file-read wat-list
    set ii ii + 1]
  file-close

  let b array:from-list n-values ii [item ? wat-list]

  while [ j < ii]
  [
    create-watersources 1                                                              ;;create
        households and place on display
    [
      set xcor (array:item b j - xmin)/(xmax - xmin) * world-width + min-pxcor
      set ycor (array:item b i - ymin)/(ymax - ymin) * world-height + min-pycor
      set source-kind (array:item b k)
    ]
    ask watersources [ setxy xcor ycor set size 1.5]

    ask watersources
    [if source-kind = 1 [set color 66] ;1 is River
    ;if source-kind = 2 [set color blue]
    if source-kind = 3 [set color 86] ;3 is MT
    ]

    set i i + 3
    set j j + 3
    set k k + 3

  ]


end


to setup-collect-freq
  ;Sets up collection frequency list using data from HHB study.  Tap-Min is the minimum number of
      days between collections, tap-max is the maximum days and hh-days can
  ;wait is the max number of days a HH can wait.  tap-min and tap-max were the min and max number
      of days reported by respondents during multiple types of questions
  ;during HHB.
```

```
;;Data is in terms of collects every X days

let collect-freq-list []

file-open "water_collect_freq.txt"          ;; open txt file containing lat/long decimal
    format coordinates for HHB households (50 entries)
while [not file-at-end?]
[set collect-freq-list lput file-read collect-freq-list]
file-close
let a array:from-list n-values 196 [item ? collect-freq-list]


ask households[

  set tap-min 99
  set tap-max 99
  set hh-days-can-wait 99

  if who < 49
  [
    set tap-min array:item a (who * 4)
    set tap-max array:item a ((who * 4) + 1)
    set hh-days-can-wait array:item a ((who * 4) + 3)
  ]
]

ask households [
  if tap-min = 99 [    ;Basically, if no tap-min has yet to be assigned
    let iii 0
    let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found.

    while [found-nearby-house = 0]   ;while no nearby HHB house has been found keep searching
        outward radially
      [
        let near-quantity 999   ;re-setting the "near" sources to 999
        ask households in-radius iii
          [
            if (tap-min != 99 and who < 49);If nearby HHB house has legit storage container tag
                use that data to set near-storage
            [
              set near-quantity tap-min
              set found-nearby-house 1
            ]

          ]
        set iii iii + 1
        if  tap-min = 99 and found-nearby-house = 1    ;Break out of the previous search and set
             the formally unspecified house to be a nearby house
          [set tap-min near-quantity]


      ]
```

```
  ]  ]

ask households [
  if tap-max = 99 [    ;Basically, if no storage-countainer has yet to be assigned
    let iii 0
    let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found.

    while [found-nearby-house = 0]   ;while no nearby HHB house has been found keep searching
        outward radially
      [
        let near-quantity 999   ;re-setting the "near" sources to 999
        ask households in-radius iii
          [
            if (tap-max != 99 and who < 49);If nearby HHB house has legit storage container tag
                use that data to set near-storage
            [
              set near-quantity tap-max
              set found-nearby-house 1
            ]

          ]
        set iii iii + 1
        if  tap-max = 99 and found-nearby-house = 1    ;Break out of the previous search and set
             the formally unspecified house to be a nearby house
          [set tap-max near-quantity]




      ]
  ];set color scale-color red tap-max 0 10
]



ask households [
  if hh-days-can-wait = 99 [    ;Basically, if no storage-countainer has yet to be assigned
    let iii 0
    let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found.

    while [found-nearby-house = 0]   ;while no nearby HHB house has been found keep searching
        outward radially
      [
        let near-quantity 999   ;re-setting the "near" sources to 999
        ask households in-radius iii
          [
            if (hh-days-can-wait != 99 and who < 49);If nearby HHB house has legit storage
                container tag use that data to set near-storage
            [
              set near-quantity hh-days-can-wait
              set found-nearby-house 1
            ]
```

```
          ]
        set iii iii + 1
        if  hh-days-can-wait = 99 and found-nearby-house = 1    ;Break out of the previous
            search and set the formally unspecified house to be a nearby house
          [set hh-days-can-wait near-quantity]




      ]
    ]
  ]


end






to setup-households [x y]

  let i 0
  let j 1
  let coord-list [ ]





  file-open "hhb_abm_gps_locations2.txt"            ;; open txt file containing lat/long decimal
      format coordinates for HHB households (50 entries)
  ;file-open "all_gps_data3.txt"                                  ;; open txt file containing
      lat/long decimal format coordinates for all households
  while [not file-at-end?]
  [set coord-list lput file-read coord-list]
  file-close

  file-open "ceramic_abm_gps_locations2.txt"      ;; txt file with all the Ceramic Filter
      locations 176 entries
  while [not file-at-end?]
  [set coord-list lput file-read coord-list]
  file-close

  file-open "remaining_abm_gps_locations2.txt"    ;185 remaining households from Jeff and Census
  while [not file-at-end?]
  [set coord-list lput file-read coord-list]
  file-close


  let a array:from-list n-values 820 [item ? coord-list] ;822 is the total number of household
      locations (50+176+185)*2 (2 is because it includes both lat and long)
```

```
  while [ j < 820] ;822 is the total number times two of the households.
  [
    create-ordered-households 1                                              ;;create
        households and place on display
    [

      set xcor (array:item a j - xmin)/(xmax - xmin) * world-width + min-pxcor
      set ycor (array:item a i - ymin)/(ymax - ymin) * world-height + min-pycor
    ]

  ask households [

    setxy xcor ycor
    set color orange
    set size 1.5
  ]



    set i i + 2
    set j j + 2
    ]


  ask households [

    ifelse random 100 <= cf-level [set has-filter 1][set has-filter 0]

      set cf-education-level 90
     ifelse SA = TRUE [set filrannum random 34][set filrannum random 21]


  ]



end

to setup-boil
  ;Sets up boiling frequencies.  boil-min and boil-max values taken from HHB surveys as min and
      max values taken from the different ways those questions were asked
  ;Data is in terms of boils every X days

  let boiling-list[ ]
  file-open "boiling.txt"        ;File with codes for
  while [not file-at-end?]
  [set boiling-list lput file-read boiling-list]
  file-close
  let a array:from-list n-values 98 [item ? boiling-list]
```

```
  let boil-freq-list []
  ask households [
    set boil-min 99
    set boil-max 99
    if who < 49;For all of the HHB households
      [
        set boil-min array:item a (who * 2)
        set boil-max array:item a ((who * 2) + 1)
      ]
  ]

  ask households [
    if boil-min = 99 [     ;Basically, if no boil-min has been defined yet
      let iii 0
      let found-nearby-house 0     ;Tags to specificy whether or not a nearby house has been found.

      while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
          outward radially
        [
          let near-storage 999    ;re-setting the "near" sources to 999
          let near-storage2 999
          ask households in-radius iii
            [
              if (boil-min != 99 and who < 49);If nearby HHB house has legit boil-min use that
                  data to set near-storage
              [
                set near-storage boil-min
                set near-storage2 boil-max
                set found-nearby-house 1

              ]

            ]
          set iii iii + 1
          if  boil-min = 99 and found-nearby-house = 1     ;Break out of the previous search and
              set the formally unspecified house to be a nearby house
            [
              set boil-min near-storage
              set boil-max near-storage2
            ]



        ]       ]


   ]

end

to setup-hw
```

```
;Sets up hand-washing frequency as the min and max number of times a day a person washes their
    hands.

let hw-list [ ]
file-open "hw.txt"        ;File with codes for hw "min" and "max" times per day
while [not file-at-end?]
[set hw-list lput file-read hw-list]
file-close
let a array:from-list n-values 98 [item ? hw-list]
let hw-freq-list []
ask households [          ;Set all equal to 99 for now as a placeholder
  set hw-min 99
  set hw-max 99
  if who < 49;For all of the HHB households
    [
      set hw-min array:item a (who * 2)            ;Extract min and max values
      set hw-max array:item a ((who * 2) + 1)
    ]
]

ask households [
  if hw-min = 99 [     ;Basically, if no hw-min/max has been defined yet
    let iii 0
    let found-nearby-house 0     ;Tags to specificy whether or not a nearby house has been found.

    while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
        outward radially
      [
        let near-storage 999    ;re-setting the "near" sources to 999
        let near-storage2 999
        ask households in-radius iii
          [
            if (hw-min != 99 and who < 49);If nearby HHB house has legit storage container tag
                use that data to set near-storage
            [
              set near-storage hw-min
              set near-storage2 hw-max
              set found-nearby-house 1
            ]

          ]
        set iii iii + 1
        if  hw-min = 99 and found-nearby-house = 1     ;Break out of the previous search and set
            the formally unspecified house to be a nearby house
          [
            set hw-min near-storage
            set hw-max near-storage2

          ]


      ]  ; if storage-container = 1  [set color 86] ;B, 1 or Closed Blue
```

```
        ;if storage-container = 2   [set color 16] ;C, 2 or Open Red
    ]
  ]


end



to setup-containers
  ;jc_total represents the biofilm layer on the inside of water storage containers, cup_total is
      the bacteria associated with the cups, container_cleaning is the
  ;number of times

  let container-list[ ]
  file-open "hhb_storage_cont.txt"       ;File with codes for the drinking water storage
      containers water from HHB 1=B (closed top), 2=C (open top)
  while [not file-at-end?]
  [set container-list lput file-read container-list]
  file-close

  let jc-total-list[ ]
  file-open "hhb_jc_total.txt"       ;File with codes for jc_total
  while [not file-at-end?]
  [set jc-total-list lput file-read jc-total-list]
  file-close

  let cup-total-list[ ]
  file-open "hhb_cup_total.txt"       ;File with codes for cup_total
  while [not file-at-end?]
  [set cup-total-list lput file-read cup-total-list]
  file-close

  let cleaning-list[ ]
  file-open "container_cleaning.txt"       ;File with codes for container_cleaning
  while [not file-at-end?]
  [set cleaning-list lput file-read cleaning-list]
  file-close
  let a array:from-list n-values 98 [item ? cleaning-list]

  let bhw-total-list[ ]
  file-open "bhw.txt"       ;File with codes for jc_total
  while [not file-at-end?]
  [set bhw-total-list lput file-read bhw-total-list]
  file-close


   ask households [
     set jc_total 99
     set cup_total 99
     set clean-min 99
     set clean-max 99
```

```
  set bhw_total 99
  if who < 49;For all of the HHB households
  [

    set storage-container item who container-list       ;Set storage containers to be those
        specified in HHB study, I am omitting Ceramic filter data because it isn't that
        accurate,
       set jc_total item who jc-total-list
    set cup_total item who cup-total-list
    set clean-min array:item a (who * 2)
    set clean-max array:item a ((who * 2) + 1)
    set bhw_total item who bhw-total-list
       ]
]
ask households [
  if storage-container < 1 [     ;Basically, if no storage-countainer has yet to be assigned
    let iii 0
    let found-nearby-house 0     ;Tags to specificy whether or not a nearby house has been found
        .

    while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
        outward radially
      [
        let near-storage 999    ;re-setting the "near" sources to 999
        ask households in-radius iii
        [
          if (storage-container = 1 or storage-container = 2 and who < 49);If nearby HHB house
              has legit storage container tag use that data to set near-storage
          [
            set near-storage storage-container
            set found-nearby-house 1
          ]

        ]
        set iii iii + 1
        if  storage-container < 1 and found-nearby-house = 1     ;Break out of the previous
            search and set the formally unspecified house to be a nearby house
        [set storage-container near-storage]



      ]  ; if storage-container = 1  [set color 86] ;B, 1 or Closed Blue
        ;if storage-container = 2   [set color 16] ;C, 2 or Open Red
  ]

]

ask households[

  ifelse (storage-container = 1)    ;If B or closed type storage container then this sets
      coliform incubation growth rate
  [              ;B or Closed Type Storage Containers
```

```
      set river-rand-number 3               ;Coliform incubation growth for River is located in
           position 3 in that vector
      set pipe-rand-number random 2 + 2     ;Coliform incubation growth for Pipe is located in
           positions 2,3 in that vector
    ]
    [                                       ;If C or Open Type Storage Containers then use different
         rate
      set river-rand-number random 3        ;Coliform incubation growth for River is located in
           positions 0,1,2 in that vector
      set pipe-rand-number random 2         ;Coliform incubation growth for Pipe is located in
           positions 0,1 in that vector
    ]

  ]



  ask households [
    if jc_total = 99 [     ;Basically, if no jc_total has been defined yet
      let iii 0
      let found-nearby-house 0     ;Tags to specificy whether or not a nearby house has been found
           .

      while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
           outward radially
        [
          let near-storage 999    ;re-setting the "near" sources to 999
          ask households in-radius iii
          [
            if (jc_total != 99 and who < 49);If nearby HHB house has legit storage container tag
                 use that data to set near-storage
            [
              set near-storage jc_total
              set found-nearby-house 1
            ]

          ]
          set iii iii + 1
          if  jc_total = 99 and found-nearby-house = 1     ;Break out of the previous search and
               set the formally unspecified house to be a nearby house
          [set jc_total near-storage]




        ]  ; if storage-container = 1  [set color 86] ;B, 1 or Closed Blue
          ;if storage-container = 2   [set color 16] ;C, 2 or Open Red
    ]

  ]



  ask households [
    if cup_total = 99 [     ;Basically, if no cup_total has been defined yet
```

```
      let iii 0
      let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found
          .

      while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
          outward radially
        [
          let near-storage 999    ;re-setting the "near" sources to 999
          ask households in-radius iii
          [
            if (cup_total != 99 and who < 49);If nearby HHB house has legit storage container tag
                 use that data to set near-storage
            [
              set near-storage cup_total
              set found-nearby-house 1

            ]

          ]
          set iii iii + 1
          if  cup_total = 99 and found-nearby-house = 1    ;Break out of the previous search and
               set the formally unspecified house to be a nearby house
          [set cup_total near-storage  ]



        ]
    ]


  ]


     ask households [
    if bhw_total = 99 [     ;Basically, if no cup_total has been defined yet
      let iii 0
      let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found
          .

      while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
          outward radially
        [
          let near-storage 999    ;re-setting the "near" sources to 999
          ask households in-radius iii
          [
            if (bhw_total != 99 and who < 49);If nearby HHB house has legit storage container tag
                 use that data to set near-storage
            [
              set near-storage bhw_total
              set found-nearby-house 1
                       ]
```

```
        ]
        set iii iii + 1
        if  bhw_total = 99 and found-nearby-house = 1    ;Break out of the previous search and
            set the formally unspecified house to be a nearby house
        [set bhw_total near-storage  ]



      ]  ; if storage-container = 1  [set color 86] ;B, 1 or Closed Blue
        ;if storage-container = 2   [set color 16] ;C, 2 or Open Red
   ]

 ]


 ask households [
   if clean-min = 99 [    ;Basically, if no cup_total has been defined yet
     let iii 0
     let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found
         .

     while [found-nearby-house = 0]   ;while no nearby HHB house has been found keep searching
         outward radially
       [
        let near-storage 999   ;re-setting the "near" sources to 999
        let near-storage2 999
        ask households in-radius iii
        [
          if (clean-min != 99 and who < 49);If nearby HHB house has legit storage container tag
               use that data to set near-storage
          [
            set near-storage clean-min
            set near-storage2 clean-max
            set found-nearby-house 1
                   ]

        ]
        set iii iii + 1
        if  clean-min = 99 and found-nearby-house = 1    ;Break out of the previous search and
            set the formally unspecified house to be a nearby house
        [
          set clean-min near-storage
          set clean-max near-storage2

        ]



       ]       ]
  ]
```

```
  if container-test = TRUE[   ;If in container-testing mode then
   ; let who-count 0

    ask households[
      ifelse random 100 < closed-percent [set storage-container 1][set storage-container 2]
      ;if storage-container = 1 [set color 14] ;Closed
      ;if storage-container = 2 [set color 84] ;Open
    ]
  ]

  if jc_test = TRUE[
    ask households [set jc_total jc_total_test]   ;Sets jc_total for all HH to be that which is
        set in the Interface if in jc_test mode
  ]
  if cup_test = TRUE[
    ask households [set cup_total cup_total_test] ;Sets cup_total for all HH to be that which is
        set in the Interface if in cup_test mode
  ]
  ;ask households[set color scale-color blue cup_total 0 1000]


end

to setup-haz

  set ecdage-list[ ]
  file-open "ecdage_jul_data_4mths.csv"        ;File with codes for
  while [not file-at-end?]
  [set ecdage-list lput file-read ecdage-list]
  file-close

  let final-list[ ]
  file-open "final_jul_data_4mths.csv"        ;File with codes for
  while [not file-at-end?]
  [set final-list lput file-read final-list]
  file-close

  let haz-list list ecdage-list final-list
  set haz-table table:make


  (foreach ecdage-list final-list
  [

   table:put haz-table ?1 ?2

  ])

  set ecdage-list-double[ ]
  file-open "ecdage_jul_data_4mths_double_cases.csv"        ;File with codes for
  while [not file-at-end?]
  [set ecdage-list-double lput file-read ecdage-list-double]
```

```
  file-close

  let final-list-double[ ]
  file-open "final_jul_data_4mths_double_cases.csv"       ;File with codes for
  while [not file-at-end?]
  [set final-list-double lput file-read final-list-double]
  file-close

  let haz-list-double list ecdage-list-double final-list-double
  set haz-table-double table:make

  (foreach ecdage-list-double final-list-double
  [

   table:put haz-table-double ?1 ?2

  ])



 end

to setup-hh-water-sources2

  let pri-water-list[ ]
  file-open "hhb_water_sources.txt"       ;File with codes for the primary water sources of the
      HHB water sources 1=River, 2=Piped, 3=MT, 4=Hose
  while [not file-at-end?]
  [set pri-water-list lput file-read pri-water-list]
  file-close

  let sec-water-list[ ]
  file-open "hhb_second_water_sources.txt"
  while [not file-at-end?]
  [set sec-water-list lput file-read sec-water-list] ;File with codes for the secondary water
      sources of the HHB water sources 1=River, 2=Piped, 3=MT, 4=Hose
  file-close


    ask households [


    if who < 49 ;For all of the HHB households
      [

        set pri-water-source item who pri-water-list       ;Set primary and secondary sources to be
             what the HHB study measured, I am omitting Ceramic filter data because it isn't that
            accurate, specifically, they seem to have mis-interpreted household taps and municipal
             taps
        set sec-water-source item who sec-water-list
        ;if pri-water-source = 4 [set color 14] ;Hose Red
        ;if pri-water-source = 1 [set color 84] ; River Blue
```

```
        ;if pri-water-source = 2 [set color 4] ;Piped Grey
        ;if pri-water-source = 3 [set color 54] ;MT Green
        ;if who < 49 [set color 130]

      ]
    ]

    ask households [

      if who > 49[
        let i 0
        ;let found 0
        loop
        [
        let nearest-household min-n-of i other households
        [distance myself]

        set pri-water-source [pri-water-source] of nearest-household
        if [pri-water-source] of nearest-household != 0 [stop]
        set i i + 1
        ]

             ]
    ]



end


to setup-hh-water-sources

  let pri-water-list[ ]
  file-open "hhb_water_sources.txt"       ;File with codes for the primary water sources of the
      HHB water sources 1=River, 2=Piped, 3=MT, 4=Hose
  while [not file-at-end?]
  [set pri-water-list lput file-read pri-water-list]
  file-close

  file-open "ceramic_primary_water_sources.txt" ;File with codes for the primary water sources of
      the Ceramic water sources 1=River, 2=Piped, 3=MT, 4=Hose
  while [not file-at-end?]
  [set pri-water-list lput file-read pri-water-list]
  file-close

  let sec-water-list[ ]
  file-open "hhb_second_water_sources.txt"
  while [not file-at-end?]
  [set sec-water-list lput file-read sec-water-list] ;File with codes for the secondary water
      sources of the HHB water sources 1=River, 2=Piped, 3=MT, 4=Hose
  file-close
```

```
file-open "ceramic_second_water_sources.txt"
while [not file-at-end?]
[set sec-water-list lput file-read sec-water-list]
file-close

ask households [
  set pri-water-source 999 ;999 is a number I assigned in the above text files and here to
      indicate that no source has been assigned to a given household
  set sec-water-source 999

  if who < 49 ;For all of the HHB households
    [

      set pri-water-source item who pri-water-list      ;Set primary and secondary sources to be
           what the HHB study measured, I am omitting Ceramic filter data because it isn't that
          accurate, specifically, they seem to have mis-interpreted household taps and municipal
           taps
      set sec-water-source item who sec-water-list

    ]
]
   ask households [

  if pri-water-source = 999 or sec-water-source = 999 [     ;Effectively, look at all households
      with pri or sec sources as yet unspecified
    let iii 0
    let found-nearby-house 0    ;Tags to specificy whether or not a nearby house has been found.
    let found-nearby-house2 0

    while [found-nearby-house = 0]    ;while no nearby HHB house has been found keep searching
        outward radially
      [
        let near-pri-water-source 999    ;re-setting the "near" sources to 999
        ask households in-radius iii
          [                                                                      ;I am not letting
              26 and 20 determine nearby houses because 26 uses the river and I am confident
              that the houses nearby probably don't use this source, also excluding 20 because
              they reported using the Pipe system which is not in the part of Tshibvumo where
              they are.
            if pri-water-source > 0 and pri-water-source < 5 and found-nearby-house = 0 and who
                < 49 and who != 26 and who != 20  ;If nearby HHB house has legit source use that
                 data to set near-pri
            [
              set near-pri-water-source pri-water-source
              ;set near-sec-water-source sec-water-source
              set found-nearby-house 1
            ]
          ]
        set iii iii + 1
        if  pri-water-source = 999 and found-nearby-house = 1    ;Break out of the previous
             search and set the formally unspecified house to be a nearby house
          [set pri-water-source near-pri-water-source]
```

```
      ]

    set iii 0                                ;Same loop as above, just for the secondary sources

    while [found-nearby-house2 = 0]
      [

        let near-sec-water-source 999
        ask households in-radius iii
          [
            if sec-water-source > 0 and sec-water-source < 5 and found-nearby-house2 = 0 and who
                 < 49
            [
              set near-sec-water-source sec-water-source
              ;set color 46
              set found-nearby-house2 1
            ]
          ]
        set iii iii + 1
        if  sec-water-source = 999 and found-nearby-house2 = 1
          [set sec-water-source near-sec-water-source]
      ]



  ]
  set today-source pri-water-source
]

if source-scenario-test = TRUE [  ;If in source-testing mode then setup houses to have one of
     four different sources according to Interface page
  let who-count 0

  if source-scenario = 1 [set river-percent 0 set pipe-percent 100 / 3 set mt-percent 100 / 3
       set hose-percent 100 / 3]
  if source-scenario = 2 [set river-percent 25 set pipe-percent 25 set mt-percent 25 set hose-
       percent 25]
  if source-scenario = 3 [set river-percent 50 set pipe-percent 50 / 3 set mt-percent 50 / 3 set
        hose-percent 50 / 3]
  if source-scenario = 4 [set river-percent 75 set pipe-percent 25 / 3 set mt-percent 25 / 3 set
        hose-percent 25 / 3]
  if source-scenario = 5 [set river-percent 100 set pipe-percent 0 set mt-percent 0 set hose-
       percent 0]
  if source-scenario = 6 [set pipe-percent 0 set river-percent 100 / 3 set mt-percent 100 / 3
       set hose-percent 100 / 3]
  if source-scenario = 7 [set pipe-percent 50 set river-percent 50 / 3 set mt-percent 50 / 3 set
        hose-percent 50 / 3]
  if source-scenario = 8 [set pipe-percent 75 set river-percent 25 / 3 set mt-percent 25 / 3 set
        hose-percent 25 / 3]
  if source-scenario = 9 [set pipe-percent 100 set river-percent 0 set mt-percent 0 set hose-
       percent 0]
  if source-scenario = 10 [set mt-percent 0 set pipe-percent 100 / 3 set river-percent 100 / 3
       set hose-percent 100 / 3]
```

```
if source-scenario = 11 [set mt-percent 50 set pipe-percent 50 / 3 set river-percent 50 / 3
    set hose-percent 50 / 3]
if source-scenario = 12 [set mt-percent 75 set pipe-percent 25 / 3 set river-percent 25 / 3
    set hose-percent 25 / 3]
if source-scenario = 13 [set mt-percent 100 set pipe-percent 0 set river-percent 0 set hose-
    percent 0]
if source-scenario = 14 [set hose-percent 0 set river-percent 100 / 3 set mt-percent 100 / 3
    set pipe-percent 100 / 3]
if source-scenario = 15 [set hose-percent 50 set river-percent 50 / 3 set mt-percent 50 / 3
    set pipe-percent 50 / 3]
if source-scenario = 16 [set hose-percent 75 set river-percent 25 / 3 set mt-percent 25 / 3
    set pipe-percent 25 / 3]
if source-scenario = 17 [set hose-percent 100 set river-percent 0 set mt-percent 0 set pipe-
    percent 0]


ask households[

  ;Setting up households to have one of four source according to the percentages on the main
      page. using who-count to go through the list so the houses are randomized
  if who-count < river-percent / 100 * 410 [set pri-water-source 1]  ;River
  if who-count >= river-percent / 100 * 410 and who-count < pipe-percent / 100 * 410 + river-
      percent / 100 * 410 [set pri-water-source 2]  ;Pipe
  if who-count >= pipe-percent / 100 * 410 + river-percent / 100 * 410 and who-count < pipe-
      percent / 100 * 410 + river-percent / 100 * 410 + mt-percent / 100 * 410  [set pri-water
      -source 3]  ;MT
  if who-count >= pipe-percent / 100 * 410 + river-percent / 100 * 410 + mt-percent / 100 *
      410 and who-count < pipe-percent / 100 * 410 + river-percent / 100 * 410 + mt-percent /
      100 * 410 + hose-percent / 100 * 410 [set pri-water-source 4] ;Hose
  set who-count who-count + 1
  if pri-water-source = 4 [set color 14] ;Hose Red
  if pri-water-source = 1 [set color 84] ; River Blue
  if pri-water-source = 2 [set color 4] ;Piped Grey
  if pri-water-source = 3 [set color 54] ;MT Green

  set today-source pri-water-source
]

ask households[
  if who-count < river-percent / 100 * 410 [set sec-water-source 1]
  if who-count >= river-percent / 100 * 410 and who-count < pipe-percent / 100 * 410 + river-
      percent / 100 * 410 [set sec-water-source 2]
  if who-count >= pipe-percent / 100 * 410 + river-percent / 100 * 410 and who-count < pipe-
      percent / 100 * 410 + river-percent / 100 * 410 + mt-percent / 100 * 410  [set sec-water
      -source 3]
  if who-count >= pipe-percent / 100 * 410 + river-percent / 100 * 410 + mt-percent / 100 *
      410 and who-count < pipe-percent / 100 * 410 + river-percent / 100 * 410 + mt-percent /
      100 * 410 + hose-percent / 100 * 410 [set sec-water-source 4]
]


]
```

```
  ask households [

    if (pri-water-source = 1);River
      [set daily-wq item random length surfwq surfwq]

    if (pri-water-source = 2 or pri-water-source = 4) ;Piped or Hose
      [set daily-wq item random length pipewq pipewq]

    if (pri-water-source = 3);MT
      [set daily-wq item random length mtwq mtwq]

  ]



end



to make-height-array
   let height-list [ ]
   file-open "boyheight.txt"                                          ;;open txt file containing WHO
       SD0 male height scores by day
   while [not file-at-end?]
   [set height-list lput file-read height-list]                  ;;looks at txt file and places new
       number at the end of the list using lput
   file-close
   set height-array array:from-list n-values 1833 [item ? height-list]    ;;covert list to height-
       array for access during height calculation

   let feight-list [ ]
   file-open "femaleheight.txt"                                       ;;open txt file containing
       WHO SD0 female height scores by day
   while [not file-at-end?]
   [set feight-list lput file-read feight-list]                  ;;looks at txt file and places new
       number at the end of the list using lput
   file-close
   set feight-array array:from-list n-values 1833 [item ? feight-list]    ;;covert list to feight-
       array for access during height calculation

   let malfeight-list [ ]
   file-open "maled_girl_growth.txt"                                  ;;open txt file
       containing WHO SD0 female height scores by day
   while [not file-at-end?]
   [set malfeight-list lput file-read malfeight-list]              ;;looks at txt file and
       places new number at the end of the list using lput
   file-close
   set malfeight-array array:from-list n-values 730 [item ? malfeight-list]    ;;covert list to
       feight-array for access during height calculation
```

```
  let malheight-list [ ]
  file-open "maled_boy_growth.txt"                                    ;;open txt file
     containing WHO SD0 female height scores by day
  while [not file-at-end?]
  [set malheight-list lput file-read malheight-list]              ;;looks at txt file and
     places new number at the end of the list using lput
  file-close
  set malheight-array array:from-list n-values 730 [item ? malheight-list]    ;;covert list to
     feight-array for access during height calculation

  let water-usage-list []
  file-open "maled_water_usage_percents.csv"
  while [not file-at-end?]
  [set water-usage-list lput file-read water-usage-list]
  file-close
  set water-usage-array array:from-list n-values 731 [item ? water-usage-list]

end
```

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