USE AND PERFORMANCE OF BIOSAND FILTERS IN POSOLTEGA, NICARAGUA

by

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ABSTRACT

An evaluation of BioSand Filters, a method of Household Water Treatment, was conducted in Posoltega, Nicaragua, with objectives of determining the long-term filtration efficiency and the rate of sustained use. Field methods included microbial and turbidity water quality testing and interviews with filter users regarding the operation, maintenance and perceptions towards the filters. Of the 234 BioSand Filters installed in 1999 and 2004, only 24 were found to still be in operation. The average filtration efficiency was found to be 98% for total coliforms, 96% for *E. coli* and 88% for turbidity. Statistically significant effects on filtration efficiency were detected for the source contamination, the inverse of the flow rate, and the standing depth of water over the sand.

A follow-up laboratory QA/QC procedure was undertaken to validate the field methods, which consisted of membrane filtration (MF) with m-coliBlue24 growth media, and SolarCult dipslides. It was found that MF with m-coliBlue24 produced useful reproducible results, and is an appropriate method for conducting field water quality testing. The dipslides were found to be an appropriate tool for testing source water quality and assessing the applicability of BioSand Filters, and may be an appropriate tool for local health representatives to promote safe water practices within the community. However, the dipslides should not be used as a presence / absence test for drinking water due to the high limit of detection.

The low rate of sustained use (10%) is mostly a result of the structural failure of the concrete walls of the filter, in particular for those filters from 2004. Anecdotal evidence suggests insufficient quality control during the construction. The filtered water and the stored post-filtered water did not meet the WHO guidelines for safe drinking water on account of the presence of *E. coli*. Also identified were improper maintenance practices and unsafe storage of post-filtered water. These problems could have been addressed through the development of a holistic water system approach, such as the World Health Organization Water Safety Plan.

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LIST OF ABBREVIATIONS

APHA	American Public Health Association
CAWST	Center for Affordable Water and Sanitation Technology
CDC	US Centers for Disease Control and Prevention
CFU	Colony-Forming Units
CIRA	*Centro para la Investigación en Recursos Acuáticos de Nicaragua* (Nicaraguan Center for Aquatic Resources Research)
DALY	Disability-Adjusted Life-Years
GM	Geometric Mean
GSD	Geometric Standard Deviation
HWT	Household Water Treatment
INETER	*Instituto Nicaragüense de Estudios Territoriales* (Nicaraguan Institute for Territorial Studies)
MF	Membrane Filtration
MINSA	*Ministerio de Salud de Nicaragua* (Nicaraguan Ministry of Health)
MPN	Most Probable Number
ND	Not Detected
NGO	Non-Governmental Organization
NTU	Nephelometric Turbidity Units
QA/QC	Quality Assurance / Quality Control
SD	Standard Deviation
SODIS	Solar Disinfection
TNTC	Too Numerous To Count
TSA	Tryptic Soy Agar
UBC	University of British Columbia
UofC	University of Calgary
UNAN	*Universidad Nacional Autónoma de Nicaragua* (National Autonomous University of Nicaragua)
USEPA	US Environmental Protection Agency
WHO	World Health Organization
WSP	Water Safety Plan

PREFACE

An evaluation of BioSand Filters, a form of Household Water Treatment, was conducted in Posoltega, Nicaragua from January to April of 2007. This was a collaboration research project between researchers at the University of British Columbia (UBC) and the Center for Affordable Water and Sanitation Technology (CAWST), with collaborative support from the Center for Aquatic Resources Research (CIRA) of the National Autonomous University of Nicaragua (UNAN) and on-the-ground support from the Ministry of Health of Nicaragua (MINSA) through the local health center of Posoltega. The motivation for the research project was as a follow-up evaluation of the BioSand Filters that were installed in 1999 as part of a relief project between CIRA, the University of Calgary and an international non-governmental organization (NGO) to provide safe drinking water to those families that were impacted by Hurricane Mitch. The purpose of the evaluation was to determine the rate of sustained use of the filters, the filtration efficiency of the filters, and assess the filters as an appropriate intervention for these communities. The research methods included community consultations, household interviews, inspections of the BioSand Filters, and field water quality testing.

The findings of the research are presented in three distinct papers, each of which has been submitted to peer-reviewed journals for publication. The first paper presents a summary of the methods used to identify and evaluate the filters that were in operation, and presents the outcome of the evaluation as the efficacy of the BioSand Filters. This paper was submitted to the Water Quality Research Journal of Canada. The second paper was an evaluation of the field water quality testing techniques used to determine the microbial contamination of the water samples, and how some of the techniques can be used to conduct such an evaluation where there is limited access to laboratory facilities and testing resources. The third paper presents an argument for the need to use a holistic system approach to the delivery of Household Water Treatment, using the findings of the BioSand Filter implementation project in Posoltega, Nicaragua as a case study.

These latter two papers were submitted to the International Journal of Environmental Health Research.

The pre-submission drafts of these three papers form the body of this thesis. This is preceded by the following introduction, which provides the global context of household water treatment, and the development of the BioSand Filter as a form of HWT technology. Some overall conclusions and recommendations for the research are presented at the end of the document. The appendix includes the raw data, sample calculations, a copy of the questionnaire used during the evaluation and the approval form indicating that this research project has been approved by the Behavioural Research Ethics Board at UBC.

ACKNOWLEDGEMENTS

I would like to acknowledge the tremendous amount of support that I have received from my supervisory committee. I want to thank Jim Atwater for challenging me to think critically at every stage of the project, while providing just enough guidance for me to go through my own learning process and reach my own conclusions. I want to thank Dr. Karen Bartlett for all of her assistance in the laboratory without which I would have been lost, and for her contagious energy and enthusiasm that she brings to every project. I want to thank Derek Baker for allowing me to benefit from his previous experience with similar studies, and for helping me to stay focused on the central issue: the provision of safe drinking water to those in need.

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I want to acknowledge the Bridge Program for providing the opportunity to undertake this interdisciplinary research project. I also want to thank my fellow colleagues in the program for sharing in all of the lessons learned along the way. A special thanks to Imelda Wong, the Bridge Program Coordinator, for taking care of all the behind-the-scenes logistics to keep us "Bridgers" happy.

I would also like to thank all of the people who contributed to making the project a success: David Bethune at the University of Calgary and the Central American Water Resources Management Network (CARA) for bringing this project to my attention and arranging the initial contacts; Katherine Vammen and Valeria Delgado at the *Centro para la Investigación en Recursos Acuáticos de Nicaragua* (CIRA) for assisting with planning and logistics in Nicaragua; the *Ministerio de Salud de Nicaragua* (MINSA) staff at the Alma Nubia López Health Center of Posoltega for their on-the-ground support including the use of the *camponera* for transportation to the rural communities, and in particular Ronaldo Hernandez for acting as our guide and assisting with the critically important introductions into the rural communities; Don Carlos

Para: Sonia Anahis Romero Peralta,

y todo el pueblo de El Trianón.

CO-AUTHORSHIP STATEMENT

Versions of three excerpts from this thesis have been submitted for publication:

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      BioSand Filters in Posoltega, Nicaragua. Water Quality Research Journal of Canada.

Vanderzwaag JC, Bartlett KH, Atwater JW and Baker D. Evaluation of field testing techniques

      used in a household water treatment study in Posoltega, Nicaragua. International Journal

      of Environmental Health Research.

Vanderzwaag JC, Bartlett KH, Atwater JW and Baker D. Failure of household water treatment in

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The need for a follow-up evaluation of BioSand Filters in Posoltega, Nicaragua was originally

brought to the attention of Jason Vanderzwaag by David Bethune of the Central American Water

Resources Management Network (CARA) at the University of Calgary, who suggested

contacting Derek Baker at the Center for Affordable Water and Sanitation Technology

(CAWST) for specific technical information regarding BioSand Filters. Under the guidance of

co-supervisors Jim Atwater and Dr. Karen Bartlett from UBC and D. Baker from CAWST,

J. Vanderzwaag developed the research program design, including water quality testing protocols

and a household questionnaire. J. Vanderzwaag conducted the field research in Nicaragua from

January to April 2007. Upon his return to Canada, J. Vanderzwaag conducted follow-up

laboratory work and data analysis, under the guidance of Dr. Bartlett. All three manuscripts and

the supporting documentation were prepared by J. Vanderzwaag, with helpful feedback provided

by J. Atwater, Dr. Bartlett and D. Baker throughout the writing process.

1   INTRODUCTION

1.1   The Case for Household Water Treatment

1.1.1   Global Water, Sanitation and Health Issues

The World Health Organization (WHO) defines "access to improved drinking water" as a source that is less than one kilometre away from its place of use, from which it is possible to reliably obtain at least 20 litres per member of a household per day, and the water exhibits microbial, chemical and physical characteristics that meet WHO guidelines or national standards on drinking water quality (WHO, 2006). Examples of access to improved water sources include piped household connections, public standpipes, boreholes, protected dug wells, protected springs and rainwater.

The WHO estimates that there are 1.1 billion people worldwide without access to improved drinking water and 2.6 billion people without access to basic sanitation such as an improved latrine (WHO, 2005). As a direct consequence of these conditions: 1.6 million people die every year from diarrhoeal diseases and 90% of these are children under 5, mostly in developing countries; 133 million people suffer from high intensity intestinal helminth infections; and there are around 1.5 million cases of clinical hepatitis A every year (WHO, 2005).

The global burden of these diseases can be quantified by the disability-adjusted life-years (DALY), a metric developed by the WHO for accounting for both death and disability caused by a disease. The DALY is the sum of the years of lost life due to premature mortality and the years lost due to disability for incident cases of the disease. In developing regions, diarrhoeal disease is the second highest cause of DALYs, accounting for 8.1% of the burden of disease within the region. Poor water supply, sanitation and personal and domestic hygiene were identified as the second highest risk factor for contributing to the global burden of disease, accounting for 94 million DALYs and 6.8% of the global total (Prüss and Havelaar, 2001).

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The impact of these diseases can be felt directly at the household and community level in developing regions. Young children suffering from illness require adult attention, and attending to illness directs already limited household and community resources away from other economic and educational activities. Thus, while waterborne illness resulting from poor water supply and sanitation is a symptom of poverty, it is also a contributing factor that needs to be addressed in these developing regions. Addressing poor water and sanitation is also critical for addressing other health issues, as stated by Kofi Annan, Secretary General of the United Nations: "We shall not finally defeat AIDS, tuberculosis, malaria, or any of the other infectious diseases that plague the developing world until we have also won the battle for safe drinking water, sanitation and basic health care" (WHO, 2005).

The importance of addressing poor water and sanitation is highlighted in Target 10 of the Millennium Development Goals: to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation (WHO, 2005). Meeting such a target requires strategies at multiple levels of government, in collaboration with agencies and organizations working at the community level to address water, sanitation and health issues.

The WHO Guidelines for Drinking Water Quality (WHO, 2006) is one of many tools that can be used by governments and other organizations working in water and sanitation projects. The guidelines provide health-based criteria for microbial, chemical and physical characteristics of drinking water quality, and provide guidance on the forms of treatment technology that can be used to achieve the criteria. In particular, the guidelines discuss the use of *Escherichia coli* (*E. coli*) as an indicator for fecal contamination in water supplies and the potential presence of enteric pathogens, and clearly state that "*E. coli* should not be present in water intended for drinking" (WHO, 2006).

The guidelines also prescribe the use of a Water Safety Plan (WSP) as a risk assessment and risk management approach that encompasses all steps in water supply from catchment to

consumer. A WSP has three key components: system assessment to determine whether the drinking water supply chain can deliver water that meets health-based targets; operational monitoring to ensure that the control measures are being implemented, and management plans that cover normal operation and incident conditions. This holistic system approach is applicable in any setting and context, with any form of water treatment and delivery technology, and as such is a valuable tool for implementing water projects in developing regions.

1.1.2 Household Water Treatment and Safe Water Storage

Household Water Treatment (HWT) is a novel approach that is being forwarded by the WHO and other water, sanitation and health policy makers worldwide as an alternative to centralized treatment and distribution systems in addressing the global issues of poor water and sanitation.

Mintz et al. (2001) discuss the challenges of providing safe drinking in developing regions of the world, including population growth, funding limitations, inadequate operation and maintenance, inadequate cost recovery, insufficient trained personnel and the inappropriateness of traditional policies, resources and technologies. They suggest that "relying only on time- and resource-intensive centralized solutions such as piped, treated water will leave hundreds of millions of people without safe water far into the future" and the recommended alternatives are "self-sustaining, decentralized approaches to making drinking water safe" (Mintz et al., 2001).

Mol (2001) argues the need for household level intervention after witnessing the failure of numerous centralized water systems in Kenya and other parts of Africa. "Many required a very high initial investment, are technically complex, need continued maintenance and were never 'owned' by the community. It is thus no wonder that most systems have failed to produce clean water for long, and now the area is littered with the remnants of failed projects: derelict pipeline systems and treatment facilities, empty water kiosks, washed-away sand dams and pumps with no spare parts." Mol suggests that the cause of failure was not necessarily the introduction of inappropriate technology or even the lack of community involvement, but rather the initial

assumption that community water systems are necessary to provide safe water. Communities are composed of widely diverse individuals, each with their own needs and agendas, which as Mol states "often leads to corruption and financial mismanagement of water committees" (Mol, 2001).

In contrast with centralized community water systems, HWT focuses on individual benefit through individual application as the cornerstone of an implemented water project. This is achieved by placing the responsibility for water treatment at the household level, wherein a family uses a household-scale technology to treat their own drinking water and store it for subsequent consumption. The technology is typically simple to use, with minimal if any financial costs to the user, and does not depend on community infrastructure.

Dr. Jamie Bartram, Coordinator for the Water, Sanitation and Health Programme of the WHO states that "there is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically reducing the risks of diarrheal disease and death. These household interventions are cost-effective, with an overall benefit of up to $60 US per $1 US invested" (Sobsey, 2002, foreword).

There are numerous forms of HWT technology that are intended to eliminate pathogens from drinking water by one of the following methods: heat and UV radiation, filtration, chemical disinfection, or some combination. The general methods are described below.

1.1.2.1   Heat and UV Radiation

Boiling is one of the most reliable methods for eliminating most pathogens from drinking water, as the vast majority of pathogenic organisms cannot withstand exposure to high heat. The US Environmental Protection Agency (USEPA) (2006) recommends boiling vigorously for one minute, or three minutes at elevations greater than 1600 m. The drawback of boiling water is that an energy source is required to produce the heat necessary for boiling. In developing countries access to energy may be limited, or is likely only available in the form of carbon-based fuels.

When biomass energy sources are burned indoors, individuals are exposed to a greater risk of respiratory illness from the smoke and fumes. Collecting and burning of wood for fuel can also have environmental consequences, including the destruction of forested lands.

Solar disinfection (SODIS) is another form of water treatment that uses solar radiation as a heat source. When applied as a form of HWT, plastic bottles are filled with water and placed in sunlight for a period of six hours. Pathogen inactivation is achieved through two mechanisms: pasteurization from the rise in water temperature and solar radiation in the UV-A spectrum (320-400 nm) (SANDEC, 2002). The advantages of SODIS are the simplicity and extremely low cost as a result of the solar energy source. The limitations of SODIS are that it is not effective for water that is high in turbidity, and does not provide any level of treatment for other forms of contaminants.

Another form of HWT that uses solar energy is solar distillation. Typically used as a form of water treatment for desalination, distillation can be effective at removing all impurities from water, including pathogens. While desalination typically requires a significant energy input to vapourize the water, distillation at the household scale can make use of solar energy to evaporate water from a shallow dish. A prismatic or conical cover over the dish allows solar radiation to penetrate to the water while trapping the vapours, which condense to water droplets and run down the interior of the cover into a collecting trough. An advantage of this technology is that the collected water will essentially be free of any impurities, and can even be used to desalinate brackish seawater. A limitation is the area required to achieve the volume of water needed by a typical household, as the daily production of distilled water is proportional to the surface area exposed to solar radiation and the ambient evaporation rate.

1.1.2.2 Filtration

Filtration is the process of passing water through a porous media, and thereby removing pathogens and other contaminants in the water. This is achieved through physical straining,

where only contaminants smaller than the pore size of the media can pass through the filter. Depending on the characteristics of the filter and the media, contaminant removal can also be achieved through mechanisms of adsorption, natural die-off, oxidation and predation. Common filtration media are sand, ceramics, activated carbon and even finely woven cloth (e.g. sari cloth).

One of the advantages of filtration as a form of HWT is that no external energy source is required, as gravity alone is sufficient to drive the water through the filter media. Furthermore, filtration can improve water quality through more than just pathogen removal; suspended sediments can be removed, and users often cite an improvement of taste. Over the course of the filter use, the filter media becomes fouled. This typically provides some benefit as the fouling causes pore sizes to become smaller, thereby achieving greater filtration efficiency, but is also a limitation because this reduces the flow rate and eventually stops the flow altogether, requiring regular but infrequent maintenance (Sobsey, 2002).

1.1.2.3   Chemical Disinfection

Chemical disinfection is the use of an agent to specifically destroy microorganisms. These chemicals typically act as oxidizing agents, oxidizing the cell membrane of microorganisms which results in a loss of structure and death by cell lysis.

The most common disinfectant used in water supplies is chlorine. When applied as a gas to water, it reacts to form a pH dependent equilibrium mixture of chlorine, hypochlorous acid and hydrochloric acid. In solution, these acids are extremely effective against nearly all pathogens. They also have a long half-life, and are thus able to provide residual protection against pathogenic recontamination. Other common chemicals used for disinfection are iodine, colloidal silver, hydrogen peroxide and ozone (Sobsey, 2002).

HWT technologies that use chemical disinfection typically come in prepackaged doses which are mixed into a specific volume of water and allowed to sit for a specified contact time to

achieve disinfection. Alternatively, household bleach, which is typically a solution of about 5% sodium hypochlorite, can also be added to water to yield hypochlorous acid (USEPA, 2006).

The advantages of chemical disinfection are that they are simple to use, are effective against most pathogens, and can generally provide a residual disinfectant against recontamination. The limitations include the fact that it is a consumable, and therefore abundant supplies must be made available locally for replenishment for users. In addition, chemical disinfection does not provide removal of suspended solids and only very minor colour reduction, and can in fact have negative impacts on the aesthetic qualities of odour and taste. Chlorine is known to be ineffective against the protozoan pathogens *Giardia lamblia* and *Cryptosporidium parvum*, and can also react with organic matter in the water to produce potentially harmful disinfection by-products (Sobsey, 2002).

1.1.2.4   Coagulation

Coagulation is the destabilization of particulate matter in suspension, which causes flocculation, the formation of larger molecules which settle out of suspension at a much faster rate than the original smaller particles. Because microorganisms typically cling to existing particulate matter in suspension, coagulation can be an effective method of removing pathogens from water. The coagulating agent typically has atomically large ions with a high electronic valence charge, to achieve greater destabilization of particulate matter. Typical coagulating agents are salts of iron (III) and alum. Extracts from the seeds of the *Moringa* species and the *nirmali* plant (*Strychnos potatorum*) have been traditionally used as a coagulating agent for treating drinking water in parts of Africa, the Middle East and the Indian subcontinent (Sobsey, 2002).

When used for HWT the coagulating agent is added directly to the container of water, which is then stirred and allowed to settle for 12-24 hours. Water containers with a narrow neck are

generally preferred for this application because the settled sediment at the bottom is less likely to be agitated and re-suspended when pouring from this type of container.

1.1.2.5   Combinations

Some of the innovative and proprietary HWT products available use some combination of the above methods to provide a multi-barrier approach to the elimination of pathogens, while offsetting some of the limitations associated with any particular method alone. Two example HWT technologies that use combined technologies are the Filtrón^{TM} made by Potters for Peace, which is a pot-shaped ceramic filter that has the interior walls treated with colloidal silver for microbial disinfection (www.pottersforpeace.org), and the PUR®-Purifier of Water developed by Proctor & Gamble in collaboration with the US Centers for Disease Control and Prevention (CDC), which combines a coagulant and a time-released chlorine disinfectant in prepackaged doses (http://www.pghsi.com/pghsi/safewater/index.html).

Different forms of HWT can also be combined in series to provide a multi-barrier approach for the elimination of pathogens. An example of this would be following water filtration with a form of chemical disinfection on the post-filtered water.

1.1.2.6   Safe Water Storage

One aspect of HWT is that the treatment must usually be applied to the drinking water at some point prior to its use, in some cases as early as 24 hours prior. This requires not only household member training to use the technology with enough frequency to ensure there is sufficient supply of safe drinking water, but also a means of safely storing the treated water until it is used. Mintz et al. (1995) discuss how water stored within the home can become contaminated by dipping contaminated vessels or hands, introducing fecal pathogens that may not have been present in the original source water, and how the choice of a storage container can change the household behaviour and thus prevent contamination. The following guidelines are

proposed by the CDC and the Pan American Health Organization in the design of a safe water storage container to be used in the home (Mintz et al., 1995):

- Be constructed of translucent high-density polyethylene plastic or similar material that is durable, lightweight, non-oxidizing, easy to clean, inexpensive, and able to be locally produced;
- Hold an appropriate standard volume (e.g. 20 L) and have a stable base and a sturdy, comfortable handle for easy carriage;
- Have a single opening 5 to 8 cm in diameter with a strong, tightly fitting cover that makes it easy to fill the container and add disinfectant but difficult to immerse hands or utensils;
- Have a non-rusting, durable, cleanable spigot for extracting water;
- Allow air to enter as water is extracted;
- Have volume indicators and illustrations of safe water handling practices displayed on the outside of the vessel.

The implementation of HWT requires not only the introduction of an appropriate water treatment technology, but also the resources at the household level to properly use the technology and to safely store the treated water.

1.1.3 Evaluation of Household Water Treatment

One of the challenges facing HWT is proving that the technology is effective at protecting public health. While the scientific principles of the many different forms and models of HWT have been verified through laboratory evaluations, there is limited data on the long term use and performance of the different technologies, including health benefits to the users (McCann, 2007). There are a growing number of publications in the literature providing scientific evidence into the effectiveness of the different forms of HWT. These publications are typically either laboratory evaluations or field evaluations, including health impact evaluations.

There is no universally agreed-upon protocol for the field evaluation of any particular HWT. The majority of published data regarding field evaluations of HWT consider the rate of sustained

use after a technology is introduced into a community, and the performance, usually measured as a reduction in an indicator organism or another metric such as turbidity between the source water and the treated water. A smaller proportion of the studies include a Health Impact Evaluation. A Health Impact Evaluation is used to compare the incidence of illness in a study population with that of a control group, and statistically analyze the results to determine whether the health changes resulting from the intervention are statistically significant.

The Center for Affordable Water and Sanitation Technology (CAWST) (2006a) recommends undertaking field evaluations to determine the following:

- Effectiveness in removing contaminants in field conditions over short and long periods of time;
- Users' perceptions and level of acceptance;
- Durability and longevity of the HWT device;
- Affordability in terms of initial and recurring costs; and
- Sustainability, meaning both demonstrated long term use and increasing usage in the community.

This field evaluation recommended by CAWST excludes health impact studies (CAWST, 2006a). Their position is as follows:

- Health Impact Evaluations are not very useful tools for evaluating water, sanitation and hygiene interventions. The results are too general to be used for analysis and planning of future projects;
- The relationship between water, hygiene and health is already well demonstrated; and
- The results [of a Health Impact Evaluation] do not mean much… if a health impact is not detected it does not mean that the water and sanitation intervention is ineffective.

On the other hand, Professor Mark Sobsey of the University of North Carolina states that Health Impact Evaluations are essential for comparative analysis between different HWT technologies, and for performing cost-effectiveness analysis. A Health Impact Evaluation can be used to estimate the reduction in diarrhoeal disease before and after a HWT intervention. This

can then be used to calculate the DALY from diarrhoeal disease, and the reduction in disease burden relative to the cost of the intervention of a particular HWT technology (BioSandFilter.org, 2004).

The different field methodologies require significantly different levels of effort to collect data for the evaluation. The data regarding use and performance as recommended by CAWST can be collected by visiting individual households and conducting interviews and water quality testing. The health impact evaluation requires detailed health data regarding incidence of gastrointestinal illness, and this type of data is generally not readily available in the remote locations in developing countries where HWT is typically implemented. Therefore data collection requires repeated household visits over a long period of time, to ask users about incidents of diarrhoea, which can be a socially awkward and taboo subject. There are also ethical considerations with the collection and storage of data regarding personal health history. Regardless of whether or not a health impact evaluation is conducted, it should be stressed that the use and performance evaluation must still be conducted prior to a health impact evaluation to ensure that the HWT intervention is in fact still in use and is performing as expected. Otherwise, it would be impossible to attribute any health impact to the particular HWT intervention.

1.2 BioSand Filtration as a Form of Household Water Treatment

The BioSand Filter is a form of Household Water Treatment (HWT) that is based on slow-sand filtration, scaled down to be used at the household level under intermittent operation. The BioSand Filter was originally envisioned and designed by Dr. David Manz while on faculty at the University of Calgary. The earliest filters were introduced in the Nandaime Valley of Nicaragua as a pilot project in 1993, and the implementation has since spread to 140,000 households across 38 countries (S. Kaczmer, CAWST, personal communication, February 1, 2008).

The following sections describe the basis for the BioSand Filter technology, and the history of its development and implementation.

1.2.1 Slow-Sand Filtration

"No other single process can effect such an improvement in the physical, chemical and bacteriological quality of normal surface waters as that accomplished by biological filtration" (Huisman and Wood, 1974). Indeed, biological filtration (or more commonly slow-sand filtration), has been shown to be an effective means of treating community water supplies since as early as 1804, when John Gibb designed and built a sand filter for his bleachery in Paisley, Scotland and sold the surplus treated water to the public (Huisman and Wood, 1974). More recent accounts into the effectiveness of slow-sand filters have demonstrated that they are capable of removing approximately 2-log concentration of heterotrophic bacteria, 3 to 4-log concentration of *Giardia lamblia* cysts, and 3 to 5-log concentration of viruses (Hendricks and Bellamy, 1991).

The slow sand filter consists of four elements: a supernatant reservoir, a bed of filter media, an underdrainage system, and a system of control valves to regulate the flow. The filter beds used in municipal water treatment systems typically vary in size between 100 m^2 and 200 m^2, and have a depth of sand between 1 m and 2 m (Pyper and Logsdon, 1991). The slow sand filter requires no external energy or pressure inputs, as the vertical flow through the filter is by gravity alone. A critical component for the purification of the raw water is the naturally occurring *schmutzdecke* (biological layer) that grows within the top depth of sand. The microbial flora that grows in the biological layer feeds on the influent nutrients in the supernatant and is instrumental in pathogen inactivation.

One of the considerations of slow sand filtration is that of regular maintenance. Over time, the growth of the biological layer plus the addition of particulate matter strained out at the top of the sand layer clogs the pores in the filter media, reducing the flow through the filter. Thus

regular maintenance is required which entails either draining and removing the top layer of sand and replacing with clean sand or *harrowing*: agitating the top layer of sand to suspend the organic material of the biological layer, allowing the sand to settle and then removing the remaining suspension. After each cleaning the filter is normally taken offline for a period to allow for the regrowth of the biological layer.

While the technology is old and relatively easy to use, it is by no means simple. The processes employed in a slow sand filter include physical straining and adsorption through the sand media, and biological processes including oxidation, natural die-off and microbial predation through the biological layer. The interaction of these interdependent forces and mechanisms during normal filter operation are the key components of the water purification through the filter. These processes are described in detail below.

1.2.1.1 Physical Straining

Huisman and Wood (1974) describe the physical processes that bring suspended particles into contact with the sand grains as screening, sedimentation, inertial and centrifugal forces, diffusion, mass attraction and electrostatic and electrokinetic attraction.

Physical screening is the retention of particles that are too large to pass through the pore spaces between the filter media. It can be shown geometrically that the pore size of a tightly packed media bed is approximately one-sixth of the effective size of the media. With a grain size of 150 μm, the filter will physically remove all particles greater than 24 μm in size at the surface.

Sedimentation is the settling action of particles as a result of differences in density between the particle and water, as predicted by Stokes' Law. In a traditional settling tank, deposits are only formed on the bottom, whereas in a filter deposits can be formed on the upward-facing surface of every sand grain. Huisman and Wood (1974) estimated this surface area to be approximately 1000 m^2 per square meter of filter, using typical values for the filter depth, the

porosity of the sand and grain size. Applying Stokes' Law, they estimate that the complete removal by sedimentation can be expected for particle sizes greater than about 4 μm.

Inertial and centrifugal forces are developed as particles move through the sand media, taking tortuous pathways around the individual sand grains. These forces increase the probability of a particle leaving the flow lines of the surrounding water and coming into contact with the sand grains (Huisman and Wood, 1974).

Diffusion is the random Brownian movement that tends to move particles from a location of high concentration to low concentration. As particulate contaminants are removed from the water stream through screening and adsorption, the concentration becomes lower near the surface of the sand grain than in the water stream. Diffusion will then cause more particles to move in the direction of the sand grain (Huisman and Wood, 1974).

The forces of mass attraction and electrostatic and electrokinetic attraction play less of a role in screening particles, but rather assist in the adsorption of particles that have come into contact with sand grains.

1.2.1.2 Adsorption

Huisman and Wood (1974) describe the forces that hold particles in place once they have made contact with sand grains as electrostatic attraction, mass attraction and adhesion.

Electrostatic attraction occurs between particles with different charges. Sand that is composed of crystalline quartz will have a negative charge, it will initially attract positively charged particles such as carbonates, flocculated particles from salts, as well as cations of iron and other metals. Negatively charged organics, including most bacteria, will initially be repelled. As the filter ripens, more particles with positive charge accumulate on the grain of sand, until oversaturation occurs and the charge is reversed. The sand grain will then accumulate particles with negative charge until oversaturation again occurs, and the process is repeated. This phenomenon occurs throughout the media, creating electrostatic fields that move charged

particles in the direction of the oppositely charged grains, where the electrostatic attraction maintains contact (Huisman and Wood, 1974).

Mass attraction is a result of Van der Waals attractive forces between molecules. This varies with the sixth power of the distance and is therefore relatively minor relative to the other forces in attracting particles, but is much more significant at keeping particles in place once contact has been made (Huisman and Wood, 1974).

As organic particulate matter accumulates through the filter media, the deposits form an ecological niche for bacteria and other microorganisms, which create a gelatinous bio-film consisting of these microorganisms, their wastes and dead cells, and partly assimilated organic materials (Huisman and Wood, 1974). In addition to the biological processes that occur within this bio-film (described below), this film decreases the pore spaces between the grains of sand which further improves the removal of particles from the raw water through the physical processes described above, and the sticky nature of the film holds these particles in place through adhesion once contact is made.

1.2.1.3   Biological Processes

The above processes of physical straining and adsorption causes a build up of organic matter within the uppermost confines of the filter media. This is called the *schmutzdecke* or biological layer, and is the most significant component of the slow-sand filter for purifying the water by breaking down organic matter and inactivating pathogenic microorganisms.

Within the biological layer, bacteria and other microorganisms derived from the influent water multiply and feed off the deposited organic particles and other organisms. The organic matter is oxidized by the bacteria to provide the energy needed for cellular metabolism, and converted into new cell material for growth. The population growth within the biological layer is limited by the nutrients in the influent water, and is accompanied by an equivalent die-off, which frees organic material to be further broken down by other organisms in the biological layer. In

this manner, the degradable organic matter from the influent water is eventually broken down into water, carbon dioxide and relatively innocuous inorganic salts (Huisman and Wood, 1974), which are then washed out through the filter.

Conditions within the biological layer are not conducive for intestinal microorganisms, such as *E. coli* and gastrointestinal pathogens. These organisms do not thrive at the water temperatures typically found in slow sand filters and there is generally insufficient organic matter of animal origin to meet their needs (Huisman and Wood, 1974). Therefore, these microorganisms are outcompeted for food and nutrients by free-living bacteria that are better adapted. Unable to thrive in these conditions, the individual microorganisms starve and naturally die off as they cannot obtain sufficient nutrients to metabolize, or are killed by other predatory organisms (protozoan and lower metazoan) within the biological layer (Huisman and Wood, 1974). The cellular material is then oxidized and metabolized to be degraded like the rest of the organic matter.

1.2.2   Intermittently Operated Slow Sand Filter

The documented high filtration efficiency of a slow sand filter, and its relative simplicity to use and operate, make slow sand filtration an attractive form of technology for water purification in rural and remote settings in developing regions of the world. Traditional slow sand filters are typically large enough to service an entire community and rely on a continuous inflow of raw water to supply the nutrients and oxygen to keep the biological layer alive. In the early 1990s Dr. David Manz developed the design for a modified slow sand filter that was small enough to be used within a single household, and provide sufficient water for the household when being used on an intermittent rather than continuous basis. In 1995, Byron Buzunis, then a Masters' student working with Dr. Manz, provided the first well-documented investigation of the household-scale intermittently-operated slow sand filter, which was later to be known as the BioSand Filter.

1.2.2.1   Design Parameters

Similar to the traditional slow sand filter, the BioSand Filter relies on slow sand filtration and the inactivation of pathogens through the biological layer for the purification of raw water. The two fundamental differences are the scale, and the intermittent flow regime. A schematic of the BioSand Filter is presented in Figure 1.1.
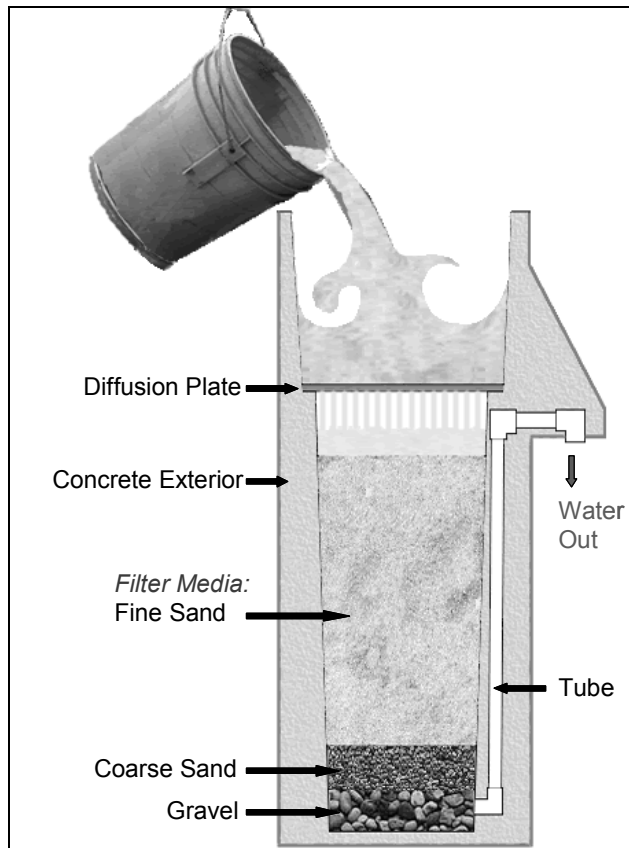
Figure 1.1   BioSand Filter Schematic. Source: Clean Water for Haiti (2003).

The filter bed of a traditional slow sand filter can vary in size between 100 m^2 and 200 m^2, and have a depth of sand between 1 m and 2 m (Pyper and Logsdon, 1991). In contrast, the BioSand Filter is an appropriate size to be used within a household, standing approximately 1 m high and typically 0.3 m to 0.4 m across. The sand bed within the filter has a surface area of between 0.06 m^2 to 0.09 m^2, and a depth of sand of approximately 0.5 m, depending upon the particular design and model. The recommended sand grain distribution is an effective size of 0.10 mm to 0.25 mm with a uniformity coefficient of 1.5 to 2.5 (CAWST, 2006b) which is

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consistent with the specifications for slow sand filters, although on the finer end of the spectrum in order to better control the flow and to account for the shallower bed depth. The sand in the BioSand Filter is underlain with two layers of gravel of increasingly larger effective diameter, to support the sand media, and an underdrain to convey the filtered water to the outlet.

The traditional slow sand filter relies on a continuous inflow of water to supply the nutrients and oxygen required to keep the microorganisms within biological layer alive. The continuous loading rate is typically between 0.04 and 0.4 m^3/hour per square meter of the surface area of the filter bed (Hendricks and Bellamy, 1991), which is controlled by either throttling an inlet control valve or by raising and lowering an outlet control weir. In contrast, a family pours in a 20 L bucket of water into the top of the BioSand Filter on a daily basis (or more frequently as required), and collects an equal volume of displaced filtered water that flows from the spout. The initial flow rate is on the approximate order of 1 m^3/m^2/hour and decreases with the falling head as the water drains from the outlet pipe, taking between 30 and 60 minutes to filter the input volume, depending upon the porosity of the filter media and maturity of the biological layer. In this configuration, the turn in the outlet pipe acts as an outlet control weir, and ensures that there is a minimum standing depth of water over the top of the sand to maintain the biological layer in an aqueous environment.

Buzunis (1995) developed a model for the diffusion of oxygen across the standing depth of water to meet the oxygen demand for the microorganisms within the biological layer during the pause period, during which there is no flow of influent water through the filter. He determined that the critical factors were the water temperature and the standing water depth, noting that "it is necessary to maintain an abundant supply of oxygen to allow the biological layer to thrive and so a minimal water layer should be used" (Buzunis, 1995). For a temperature regime of around 30ºC, which is typical for ambient conditions in tropical regions, Buzunis recommends a standing depth of 5 cm to ensure that sufficient oxygen reaches the biological layer to keep the

aerobic microorganisms alive and prevent the development of anaerobic conditions within the filter.

With the standing depth of water over the top of the sand minimized, there is little protection for the biological layer against being disrupted when the influent water is poured into the top of the filter. For this reason, the BioSand Filter design also entails a diffuser plate which significantly reduces the turbulence induced by the pouring action. The diffuser plate is typically made of plastic or metal, and sits flat inside the filter above the standing water, tight against the filter walls to prevent short-cutting. A series of tiny holes are punched through the plate material to slow the water and concentrate it into laminar streams, which reduces the physical disruption to the biological layer for the brief seconds before the plate is submerged, at which point the biological layer is well protected against physical disruption.

The other design parameter of the BioSand Filter is the selection of the construction materials. The structural walls and base of the filter housing are typically constructed from concrete, although other materials such as plastic have been used. The advantages of concrete are that the component materials (cement, sand, gravel and water) can be found almost anywhere in the world, and the structure is typically very rigid and durable, provided that it is built and cured properly. The final product can be quite heavy however, weighing between 75 and 150 kg before the sand media is added. The concrete filters are cast using a steel mold, which must be fabricated *a priori* according to the specifications for the particular filter design. One face of the filter typically features an extrusion or "nose" that encases the turn of the outlet pipe and spout. The outlet pipe is typically plastic pipe or tubing. Filters typically also have a wooden lid, to protect the top of the filter from dust, sunlight, insects and animals.

1.2.3　Evaluation of the BioSand Filter

As discussed previously, the evaluation of HWT can be divided between laboratory evaluations, field evaluations and health impact evaluations. The pertinent publications relating to the BioSand Filter in these categories are discussed below.

1.2.3.1　Laboratory Evaluations

Byron Buzunis (1995) demonstrated in a laboratory setting that the BioSand Filter was capable of removing an average of 96% of fecal coliforms. This testing was performed over a 32 day run (following a 10-day ripening period), using a combination of duck pond and river water as the influent source.

To test the ability of the BioSand Filter to remove parasitic cysts and toxicants and provide a degree of safety to those drinking the filtered water, a number of researchers at the National Water Research Institute of Environment Canada challenged the filter with inoculated water samples of known concentrations of parasites and organic and inorganic toxicants. Known as the Toxicant and Parasite Challenge, this laboratory evaluation demonstrated that the filter was indeed capable of removing "100% of *Giardia* cysts, 99.98% of *Cryptosporidium* oocysts, and 50–90% of organic and inorganic toxicants when administered in concentrations varying from 10-100x environmental pollution levels" (Palmateer et al., 1999). This is perhaps the most commonly cited laboratory evaluation of the BioSand Filter for demonstrating its efficacy as an intervention for the protection of human health.

1.2.3.2　Field Evaluations

The earliest BioSand Filters were introduced to rural communities in the Nandaime Valley of Nicaragua in 1993. Shortly after the filters were installed, water quality testing was conducted to determine if the filters operated in the field as expected. The results indicated that the filters were removing between 99.1% and 99.8% of fecal coliforms after two months of operation (Manz et al., 1993)

With the demonstrated success of the BioSand Filter, different aid organizations began introducing them to other rural and remote locations around the world in an effort to provide clean drinking water to people in need. A number of these interventions included water quality testing to evaluate the BioSand Filter in the field, the results of which are presented in Table 1.1. The results from the table demonstrate that the BioSand Filter was consistently capable of removing between 90 and 99% of microbial contaminants in the field.

Table 1.1   Previous Field Evaluations of the BioSand Filter

Reference	Year	Organization	Country	Time Since Installation	Indicator Organism	Removal Rate
Manz et al	1993	University of Calgary	Nicaragua	3 to 8 weeks	Fecal coliform	99%
Buzunis	1995	University of Calgary	Nicaragua	3 weeks	Fecal coliform	97%
Baughen et al	1999	University of Calgary	Nicaragua	1 month	Fecal coliform	80%
Mol	2001	Medair	Kenya	3 weeks	Fecal coliform	93%
Dies et al.	2003	Clean Water for Nepal	Nepal	"Recently"	*E. coli*	95%
Bojcevska & Jergil	2003	Uppsala University	Mozambique	1 month	Cyanobacteria	96%
Fewster et al.	2004	Bushproof; Medair	Kenya	2.5 to 4 years	Fecal coliform	70% < 10 cfu/100mL
Stauber et al.	2006	University of North Carolina - Chapel Hill	Dominican Republic	1 year	*E. coli*	94%
Duke et al.	2006	University of Victoria; CAWST	Haiti	5 years	*E. coli*	98.5%
Earwaker	2006	Cranfield University – Silsoe	Ethiopia	5 to 7 years	*E. coli*	88%

Much of the field data that is available is in the form of field reports from the implementing organizations, who typically undertook limited water quality testing to meet requirements from the funding agencies to demonstrate that the filters were successful. As a result, the majority of the testing was done on filters that had only recently been installed, and thus there is limited data regarding the long term effectiveness of the BioSand Filter. In addition, these field reports did not typically undergo any peer review process. It is only within the last few years that papers

have been published in peer-reviewed journals that investigate the long-term effectiveness of the BioSand Filter in field conditions.

1.2.3.3   Health Impact Evaluations

A Health Impact Evaluation of BioSand Filters in the Dominican Republic was recently completed by researchers from the University of North Carolina. About 150 households were monitored for 4 months before they were given a BioSand Filter, to assess the baseline rate of diarrhoeal illness. Then, about half of the households were given BioSand Filters and were monitored for another six months. The initial analysis showed that the BioSand Filter reduced diarrhoeal disease among household members by 30-40%, in particular among highly vulnerable young children less than five years old (Sobsey, 2007). This is the only known Health Impact Evaluation that has been conducted in regards to the BioSand Filters.

1.3   Research Question

The Municipality of Posoltega, located in the northwest of Nicaragua, was hit particularly hard by Hurricane Mitch in 1998; heavy rains triggered a landslide from La Casita volcano which killed over two thousand people, and displaced thousands more. A joint project between CIRA, the University of Calgary (UofC) and an international non-governmental organization (NGO) was initiated to bring clean water to those impacted by the hurricane. This project included delivering 34 BioSand Filters to impacted families in the rural community of El Trianón (Baughen et al., 1999). In 2004, this same NGO returned to Posoltega to deliver 200 more filters, replacing some of the filters in El Trianón and delivering new filters to the families in the rural communities of San Gilberto, Posolteguilla, Buenos Aires, El Mojón and San Agustín.

To provide further evidence into the long term efficacy of the BioSand Filter, a study was proposed to evaluate the filters that were installed in 1999 and 2004 in Posoltega. The objectives of the study were as follows:

- Characterization of the physical condition and operation of the BioSand Filters 8 years and 3 years after installation (i.e. post-1999 and 2004 respectively);
- Determination of the microbial and turbidity removal efficiency of those BioSand Filters still in operation;
- Evaluation of the BioSand Filter as an intervention for the protection of human health within the rural communities of Posoltega, Nicaragua.

This study is unique because the ages of the filters (8 years and 3 years) provide insight into the long term filter performance, as well as how this may change over time in otherwise constant conditions within the community. Furthermore, the availability of the evaluation in 1999 provides a point of reference in evaluating the filter performance.

This study was undertaken by researchers from the University of British Columbia, with collaborative support from the Center for Affordable Water and Sanitation Technology (CAWST) and the Center for Aquatic Resources Research (CIRA) at the National Autonomous University of Nicaragua (UNAN). On-the-ground support was also provided by the Nicaraguan Ministry of Health (MINSA) through the Alma Nubia Health Center in Posoltega.

The findings of the research are presented in three separate papers. The first paper presents a summary of the methods used to identify and evaluate the filters that were in operation, and presents the outcome of the evaluation of the use and performance of the BioSand Filters. The second paper presents an evaluation of the field water quality testing techniques used to determine the microbial contamination of the water samples, and how some of the techniques can be used to conduct such an evaluation where there is limited access to laboratory facilities and testing resources. The third paper presents an argument for the need to use a holistic system approach to the delivery of Household Water Treatment, using the findings of the BioSand Filter implementation project in Posoltega, Nicaragua as a case study.

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2 LONG-TERM PERFORMANCE AND USE OF BIOSAND FILTERS IN POSOLTEGA, NICARAGUA

2.1 Introduction

Access to clean water, free of contaminants and pathogens, is essential for human life, and vital for the development of healthy communities. Nonetheless, there are 1.1 billion people worldwide without access to safe drinking water and there are 1.6 million deaths every year attributable to lack of access to safe drinking water and basic sanitation; 90% of these are children under the age of five (World Health Organization [WHO], 2005). The majority of these cases are in rural areas of developing countries, where centralized distribution systems do not exist or are unable to provide clean water to the community. A novel approach that has been forwarded by the WHO and other water, sanitation and health policy makers worldwide is Household Water Treatment (HWT), where a family takes responsibility for treating their own drinking water through the application of a household-based technology. Dr. Jamie Bartram, Coordinator for the Water, Sanitation and Health Programme of the WHO states that "there is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically reducing the risks of diarrheal disease and death. These household interventions are cost-effective, with an overall benefit of up to 60 US$ per 1 US$ invested" (Sobsey, 2002, foreword).

The BioSand Filter is one type of household water treatment technology. Developed in the 1990s by Dr. David Manz while on faculty at the University of Calgary (UofC), the BioSand Filter is essentially an intermittently-operated, small-scale, slow sand filter. The low construction and installation costs, minimal maintenance requirements and the fact that it can be used in the

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absence of any other infrastructure make it an appropriate technology for application in remote and rural locations of developing countries.

Traditional slow sand filters can vary in size between 100 m^2 and 200 m^2, and have a depth of sand between 1 m and 2 m (Pyper and Logsdon, 1991). The treatment process depends on the naturally occurring biological layer or s*chmutzdecke* that develops within the top depth of sand for the inactivation of influent water borne pathogens through straining, predation, adsorption and natural die-off. The filter media is typically very fine sand that is used to structurally support the biological layer and to filter out suspended particles and organic material of the passing water. The filter media is underlain by two increasingly larger-sized granular underdrain layers with an embedded perforated drain pipe that conveys the water to an outlet chamber. An overflow weir keeps the hydrostatic water level in the filter above the top of the sand, maintaining the biological layer in an aqueous environment. Traditional slow sand filters have been shown to achieve removal efficiencies on the order of 98% for fecal coliforms when operated at a loading rate of 0.4 m^3/m^2/hour, and even higher efficiencies at lower loading rates. (See Hendricks and Bellamy, 1991; Pyper and Logsdon, 1991 for an in-depth review.)

The BioSand Filter is essentially a scaled-down version of a traditional slow sand filter to a size appropriate for a single household (Manz et al., 1993; Buzunis, 1995). While there are numerous designs available, they are generally 0.3 m to 0.5 m across and stand approximately 1 m high. The filter bodies can either be made of concrete or plastic, and the body can either be circular or square. An outlet pipe acts as the overflow weir, where the turn in the pipe determines the height of standing depth of water within the filter when there is no flow. In concrete bodies the outlet pipe is typically cast into the wall and the turn and spout are cast into a special feature called the nose; in plastic filters the outlet pipe is generally external to the body. A schematic of the BioSand Filter is displayed in Figure 2.1.
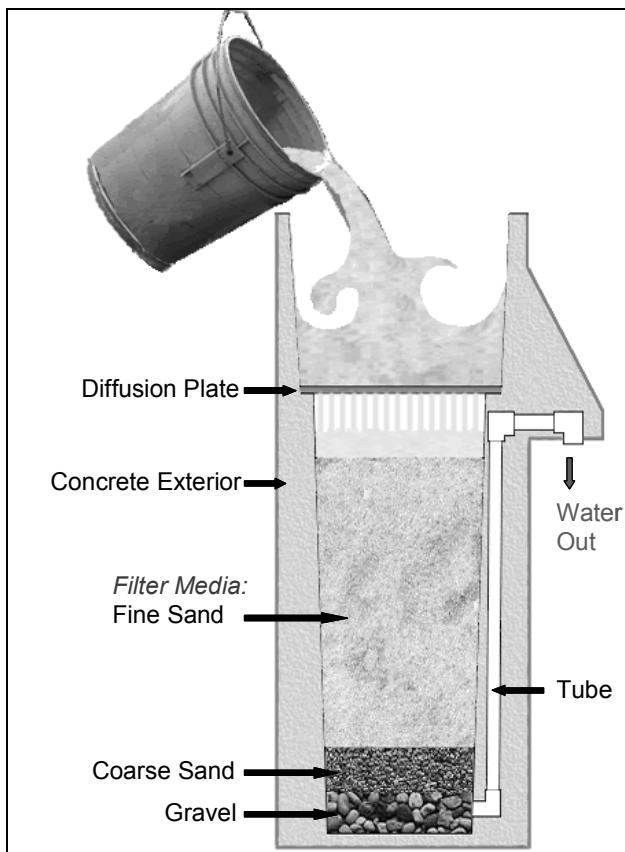
Figure 2.1   Schematic of BioSand Filter. Source: Clean Water for Haiti (2003).

In a traditional slow sand filter, the continuous supply of influent water provides the nutrients and oxygen required to keep the flora in the biological layer alive. By contrast, in a BioSand Filter the flow is applied intermittently, where the family's daily water needs are poured into the top of the filter as necessary, typically from 20 L buckets used to transport the water from the well. Buzunis (1995) investigated the transfer of oxygen across the standing water depth and demonstrated that this was sufficient to keep the biological layer alive during the pause periods provided that the depth of water was kept to a minimum. A diffuser plate was added to the design to minimize disturbance to the top layer of the sand and damage to the biological layer when the influent water is poured into the top of the filter.

Over time, the build-up of the biological layer plus the addition of particulate matter strained out at the top of the sand layer clogs the pores in the filter media, reducing the flow through the filter. This is part of the normal operation of a slow sand filter and is addressed through regular

maintenance by either draining and removing the top layer of sand and replacing with clean sand or by *harrowing*: agitating the top layer of sand to suspend the organic material of the biological layer, allowing the sand to settle and then removing the remaining suspension. After each cleaning the filter is normally taken offline for a period to allow for the regrowth of the biological layer. For the BioSand Filters, users are generally instructed to use a "swirl and dump" method akin to harrowing, where the standing water is agitated by hand to suspend the particulate matter and the dirty water is scooped out with a cup (Center for Affordable Water and Sanitation Technology [CAWST], 2006). As each family typically has only one filter they must either seek alternative treatment methods or drink water that has been treated to a lower standard during the time period following the maintenance while the biological layer is ripening. For this reason, CAWST recommends filter users disinfect post-filtered water; however, it has been found that this is rarely done in practice (Duke et al., 2006). A strategy to address this issue has not been thoroughly discussed in the published literature regarding the BioSand Filters.

The effectiveness of the BioSand Filter has been demonstrated in laboratory studies to remove 97% of fecal coliforms, and greater than 99.98% of *Giardia* cysts and *Cryptosporidium* oocysts (Palmateer et al., 1999). The effectiveness has also been investigated in a number of field studies, as displayed in Table 2.1. Furthermore, there is health-based evidence that the filter can reduce diarrheal disease by an estimated 30 percent to 40 percent, particularly among highly vulnerable young children less than 5 years old (Sobsey, 2007).

Table 2.1   Previous Field Evaluations of the BioSand Filter

Reference	Year	Organization	Country	Time Since Installation	Indicator Organism	Removal Rate
Manz et al	1993	University of Calgary	Nicaragua	3 to 8 weeks	Fecal coliform	99%
Buzunis	1995	University of Calgary	Nicaragua	3 weeks	Fecal coliform	97%
Baughen et al	1999	University of Calgary	Nicaragua	1 month	Fecal coliform	80%
Mol	2001	Medair	Kenya	3 weeks	Fecal coliform	93%
Dies et al.	2003	Clean Water for Nepal	Nepal	"Recently"	*E. coli*	95%
Bojcevska & Jergil	2003	Uppsala University	Mozambique	1 month	Cyanobacteria	96%
Fewster et al.	2004	Bushproof; Medair	Kenya	2.5 to 4 years	Fecal coliform	70% < 10 cfu/100mL
Stauber et al.	2006	University of North Carolina - Chapel Hill	Dominican Republic	1 year	*E. coli*	94%
Duke et al.	2006	University of Victoria; CAWST	Haiti	5 years	*E. coli*	98.5%
Earwaker	2006	Cranfield University – Silsoe	Ethiopia	5 to 7 years	*E. coli*	88%

As indicated in Table 2.1, the majority of the studies determined that the BioSand Filter is capable of providing between one and two logs of reduction (90% to 99%) of fecal coliforms, *E.coli* or other bacteriological species. As indicator organisms for potential fecal-derived pathogens, this provides evidence into the effectiveness of the BioSand Filters as a human health intervention for the provision of clean drinking water. The majority of these field evaluations were conducted after a relatively short time period had passed, likely as part of the reporting requirements for the implementation program, and the evaluation was conducted immediately following a period given to allow the biological layer to ripen. Only within the last few years have studies begun to emerge providing evidence about the long term effectiveness of the BioSand Filter in the types of conditions encountered in the homes and communities where they are installed.

To provide further evidence into the long term removal efficiency of the filters, a study was conducted on filters that were installed in 1999 and 2004 in Posoltega, Nicaragua; this is the

same location of the short-term evaluation conducted in 1999 by Baughen et al. from UofC listed in Table 2.1. This study is unique because the ages of the filters (8 years and 3 years) provide insight into the long term filter performance, as well as how this may change over time in otherwise constant conditions. Furthermore, the availability of the evaluation in 1999 provides a point of reference in evaluating the filter performance.

The objectives of the study were:

- Characterization of the physical condition and operation of the BioSand Filters 8 years and 3 years after installation (i.e. post-1999 and 2004 respectively);
- Determination of the microbial and turbidity removal efficiency of those BioSand Filters still in operation;
- Evaluation of the BioSand Filter as an intervention for the protection of human health within the rural communities of Posoltega, Nicaragua.

Presented in this Chapter is the performance of the BioSand Filter, evaluated as the bacteriological and turbidity removal efficiency, and the sustained use of the filters. Chapter 3 presents an evaluation of the field water quality testing methodology, and Chapter 4 presents an evaluation of the BioSand Filter as an intervention for providing safe drinking water in the rural communities of Posoltega.

2.2   Materials and Methods

The field investigation was conducted during the period of January 15 to April 15, 2007 by researchers from the University of British Columbia, with collaborative support from CAWST, the *Centro para la Investigación en Recursos Acuáticos* (Center for Aquatic Resources Research ofNicaragua, CIRA) of the *Universidad Nacional Autónoma de Nicaragua* (National Autonomous University of Nicaragua, UNAN) and the *Ministerio de Salud de Nicaragua* (Nicaraguan Ministry of Health, MINSA).

The study consisted of a systematic identification of where BioSand Filters were installed. At households where the filters were still in operation, water quality testing was conducted on the

source water and filtered water to determine the filter efficiency. This data was supplemented with a questionnaire regarding the use of the BioSand Filter and other water and sanitation practices within the household.

2.2.1 Background

In the rural communities of the Municipality of Posoltega, there is little access to community infrastructure including drinking water distribution systems. Families typically rely on individual hand-dug and shallow wells for their source water. Previous studies have shown these wells to be contaminated with pathogens and pesticides (CIRA, 1999a; b). This region was hit particularly hard by Hurricane Mitch in October 1998, when heavy rains caused widespread flooding and triggered a landslide from the La Casita volcano which buried two villages, killing approximately 2500 people.

As part of the relief effort following Hurricane Mitch, 34 BioSand Filters were delivered to families in the community of El Trianón in 1999. This was a joint effort between CIRA, UofC, and an international non-governmental organization (NGO). During this initial installation, the NGO manufactured the filters at their facility in Managua, Nicaragua and delivered them to the community (Baughen et al., 1999). These filters were a combination of plastic and concrete structures. In 2004, this same NGO returned to Posoltega to install 200 more filters, replacing some of the filters in El Trianón and installing new filters in the communities of San Gilberto, Posolteguilla, Buenos Aires, El Mojón and San Agustín. During this second round of installation, all of the filters were made of concrete and were constructed at the local health center in the town center of Posoltega. Community members participated by providing manual labour for the construction under the direction of the NGO. A map showing a layout of Posoltega and identifying the communities where filters were installed is included in Figure 2.2.
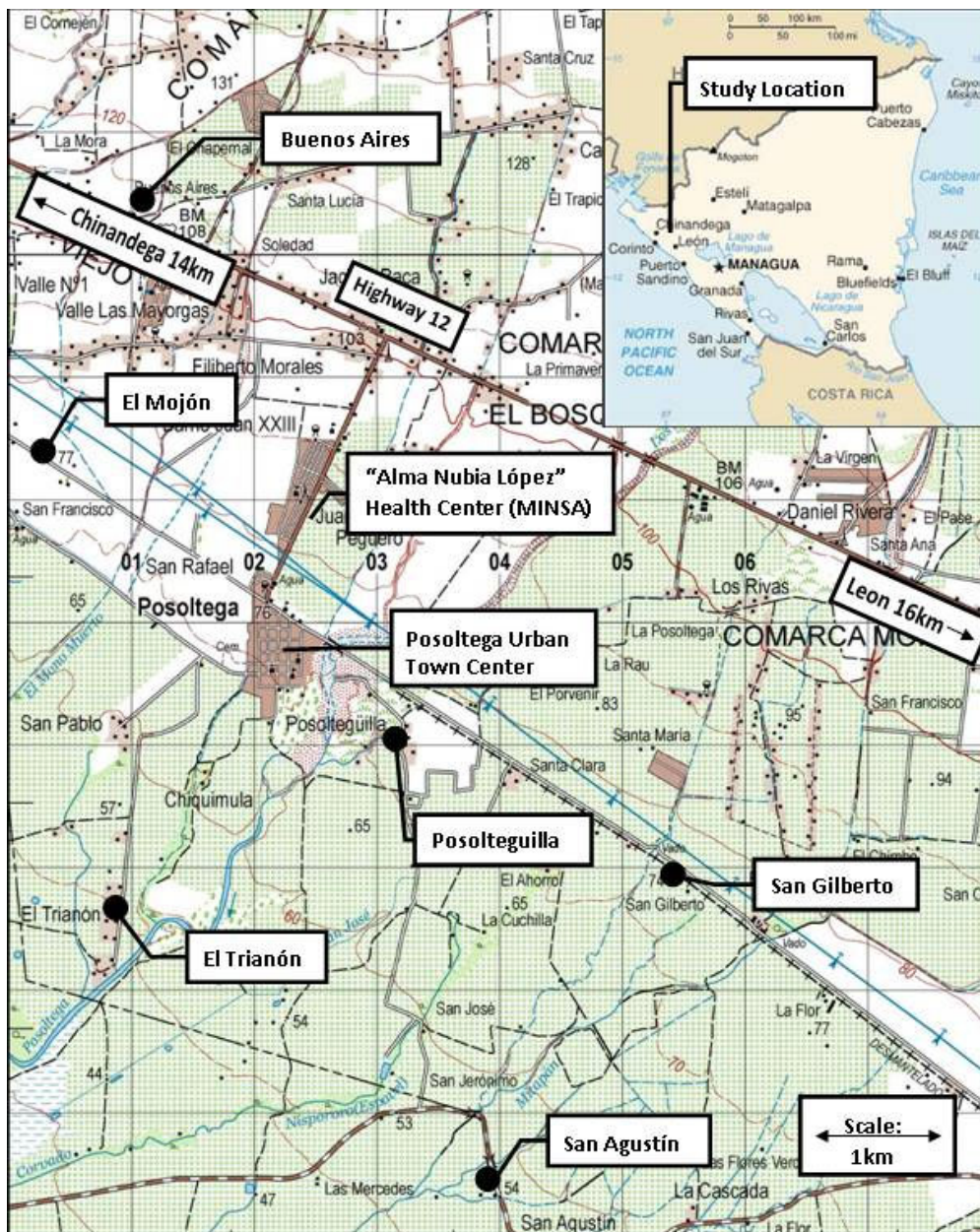
Figure 2.2   Map of Posoltega and Study Communities. Sources: US Dept of State (2007) and INETER (2006).

2.2.2   Household Identification

The research team visited the six communities where the filters were installed in order to identify those that were still in operation. The research team visited every household in the community of El Trianón, including the more remote hamlets of Corcovado and Monte Verde, to identify filters that were still in operation and determine the failure mechanism in those that were

not in operation. In the communities of San Gilberto, Posolteguilla, Buenos Aires and El Mojón, the failure rate of the filters was so high that those individual houses with working filters was common knowledge and were identified through communication with community members. In addition, approximately half of all households that had received filters were visited to determine the failure mechanisms of the other filters. In San Agustín a meeting with the community leader revealed that there was not a single filter in use in the entire community, and that all filters had failed due to the cracked concrete structure. The total number of households identified throughout the entire Municipality of Posoltega where BioSand Filters were found to be in use was 24.

All 24 households with working filters were included in the filter evaluation component of the study. In addition, nine of these households were selected for two more follow-up visits for a total of three visits each to conduct an additional series of water quality testing in order to provide a level of confidence in the results and estimate the variability in the results over the time period between visits. These nine households were selected to provide a balance of different types of filters (plastic or concrete), of different ages, from different communities and to cover a range of water quality results encountered during the initial visits.

Gaining consent of the household members to participate was done in two steps. During the initial visit verbal consent was obtained to return at a later date in order to undertake the data collection activities. Upon return, consent was again verbally obtained and evidenced by the implied consent in responding to the questionnaire.

2.2.3   Questionnaire and Observational Data

A questionnaire was administered by the interviewer at each household, typically with the female head of household. The interview was conducted in Spanish and consisted of 43 questions covering family demographic information, water use, operation of the BioSand Filter and sanitation practices. Additional observational data was recorded regarding house

construction materials and layout, condition of the well and latrine, and the general level of hygiene in the home.

An inspection of the condition of the BioSand Filter was also conducted. This included checking the integrity of the structure for cracks and leaks, ensuring the diffuser plate and lid were in place, and measuring the standing depth of water and the flow rate. The standing depth of water over the top of the sand inside the filter was measured when there was no flowing water and before adding any water to the filter. The flow rate through the filter was estimated by recording the time to fill a 250 mL cup with filtered water. The flow rate through the filter is not constant but will decrease with the falling head over the standing water depth as the water drains out of the filter. Therefore, this test was performed immediately after pouring a 20 L bucket of water into the top of the filter. The volumetric flow rate was then normalized by the cross-sectional area of the sand surface, approximately 0.06 m^2 for the square concrete filter (24 cm x 24 cm) and 0.09 m^2 for the round plastic filters (33 cm diameter), to arrive at a flow-through rate in $m^3/m^2/hour$.

2.2.4   Water Quality Testing

The evaluation of filter efficiency was based on bacteriological removal and turbidity removal through the filter. The indicator organisms selected for this study were total coliforms, representative of the total load of naturally occurring heterotrophic bacteria in a water sample, and *Escherichia coli* (*E. coli*), as an indicator of the possible presence of fecal-derived pathogenic organisms. The WHO explicitly states that *E. coli* "should not be present in drinking-water" (WHO, 2006) and as such testing for this indicator organism allows for comparison to this WHO standard.

Samples were taken from the source water before it was introduced into the top of the filter, and of the filtered water immediately leaving the spout of the filter. A third sample was taken from the stored filtered water currently being used as the family's source of drinking water to

evaluate the entire delivery system in its ability to provide clean drinking water, a discussion of which can be found in Chapter 4.

Membrane Filtration (MF) was used to test the water for coliform bacteria. The MF technique used was based on Standard Method 9222 Membrane Filter Technique for Members of the Coliform Group (APHA, 1998). The equipment used was the Potatest WE10005 (Wagtech International, Berkshire, UK). This equipment allows for the membrane filtration to take place in the field rather than having to transport water samples to a central laboratory facility. Field sterilization of the equipment was achieved through the combustion of methanol as per the manufacturer's operation manual (Wagtech, n.d.). A vacuum hand pump was then used to draw a specific volume of water through a membrane filter of pore size 0.45 µm, resulting in the microorganisms being trapped on the membrane. The membranes were then placed inside sterile Petri dishes on a growth pad that had been saturated with 2 mL of m-coliBlue24 growth media (Hach, Loveland, Colorado). This enzyme specific media allows the differentiation of total coliforms and *E. coli*, while suppressing the growth of non-coliform organisms (Hach Analytical Procedures, 1999). The Petri dishes were transported to the laboratory at the local health center to be incubated at 35°C for 24 hours. After the incubation period the colonies were enumerated with the assistance of a low-powered microscope.

A variation from the Standard Method was the filtration of smaller volumes of test water where the anticipated number of organisms in 100 mL would be too high to count on the membrane filter to produce useful results. Sample volumes of both 1 mL and 10 mL were used of the source water, and sample volumes of both 10 mL and 100 mL were used of the filtered and stored water. Membrane filtration across the two orders of magnitude improved the probability of achieving useful results over four or more possible orders of magnitude of bacteriological contamination, while the counts between the orders of magnitude provided a degree of confirmation of the procedures and results.

Two blank samples per day were taken for quality control, representing 11% of all samples. Duplicates were not explicitly taken, however the two samples at two orders of magnitude provided a level of confirmation of the field procedures and results. Furthermore, a follow-up QA/QC investigation was undertaken at the UBC School of Occupational and Environmental Hygiene microbiology lab to verify the procedures under a variety of different conditions with different organisms. The results of this QA/QC, including a discussion on the variation from the Standard Method describe above, are detailed in Chapter 3.

The Turbidity Meter Wag-WT3020 (Wagtech International, Berkshire, UK) was used to measure turbidity of the water samples in the field. Because of variations in the measured turbidity for any one sample, at least five readings were recorded for every sample, and the geometric mean of these readings was reported and used for subsequent analysis. This instrument was calibrated every day using the supplied control vials.

2.2.5   Statistical Methods

The filter efficiency was computed as a log reduction (LR) from the source contaminant metric to the filtered metric. The LR is a more useful representation of filter efficiency than percentage removal for statistical analysis because it includes the logarithmic transformation of the log-normally distributed water quality results, and therefore will better follow a normal distribution. Furthermore, the additive property of LR values makes them more appropriate for using linear statistical correlation models to determine trends in the data than percent removal. The equation for LR, given a source value of S and filtered value F, and its relationship to the percentage removal efficiency (*Eff*) is:

$$LR = \log\left(\frac{S}{F}\right) = -\log(1 - \mathit{Eff}) \qquad \textbf{(1)}$$

$$\mathit{Eff} = \frac{S - F}{S} = 1 - 10^{-LR} \qquad \textbf{(2)}$$

Student's t-test (two-tailed heteroscedastic) was used to determine the statistical significance of the difference between two means when the log-reduction data was separated by a binary or categorical variable. This was done to test the hypothesis that filtration efficiency was influenced by any of the operational variables collected during from the household interview and filter inspection. For continuous independent variables, the coefficient of determination (R^2) was computed and used to determine the statistical significance.

2.3 Results and Discussion

2.3.1 Water Quality Results

All of the bacteriological and turbidity results were found to vary over several orders of magnitude across the different records. The distribution of each series approximated a log-normal distribution, and therefore each series was logarithmically transformed prior to performing any statistical analysis. The results of the water quality analysis are included in Figure 2.3, where the geometric mean for total coliform, $E.\ coli$ and turbidity are displayed for the source water and the filtered water. The error bars indicate a factor of one geometric standard deviation.
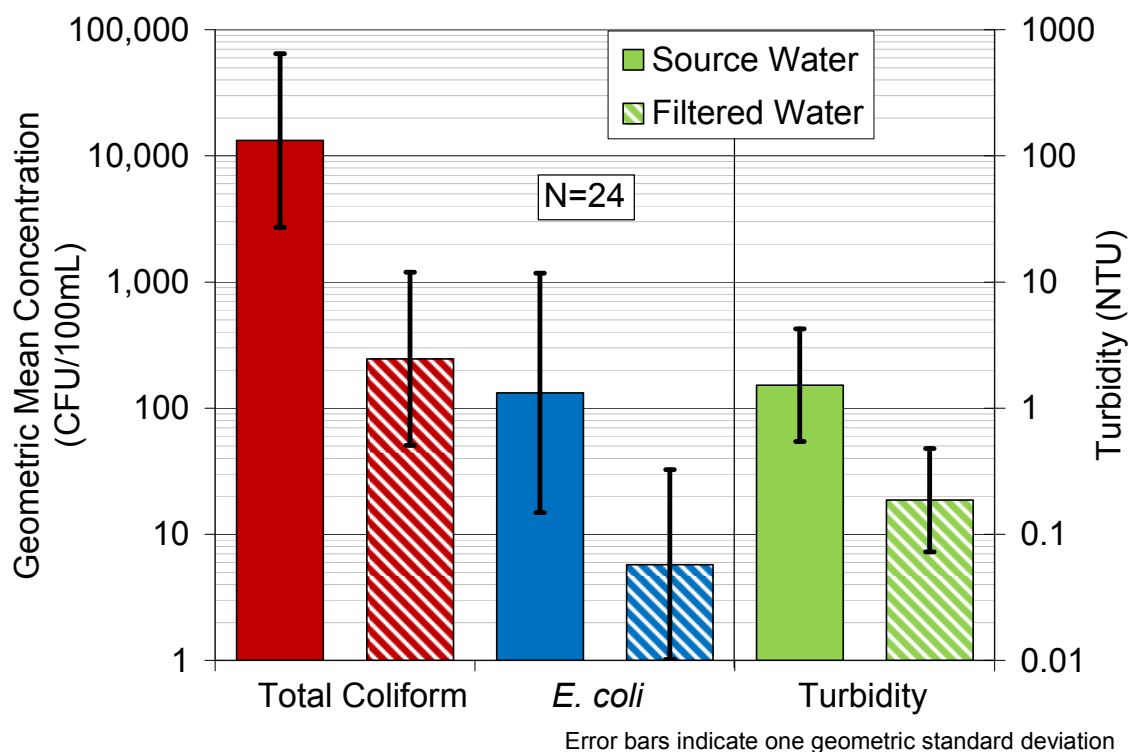
Figure 2.3   Source and Filtered Water Quality

In general, the filtered water does **not** meet the World Health Organization guidelines for drinking water quality, which states that *E. coli* must not be detectable in any 100 mL sample (i.e. 0 cfu/100mL) in water directly intended for drinking (WHO, 2006). Furthermore, only about 70% of the results yielded less than 10 cfu/100mL *E. coli* in the filtered water. This indicates that the BioSand Filter alone is not sufficient to provide clean drinking water in this situation, and that a form of additional treatment involving disinfection is required.

2.3.1.1   Filter Efficiency

The arithmetic mean of the log reduction across the filter was 1.67 (SD = 1.07) for total coliforms, 1.36 (SD = 0.82) for *E. coli* and 0.91 (SD = 0.63) for turbidity. When expressed as a percentage removal, the average filter efficiency was 98% for total coliforms and 96% for *E. coli*. The filter efficiency was found to be 88% for turbidity. Given that the source turbidity was generally quite good with 48% reporting below 1.0 NTU and 67% reporting below 3.0 NTU, the expectation is that the filter would be at least as effective for more turbid source water.

The removal efficiency of 98% for total coliforms and 96% for *E. coli* are within the expected range of removal efficiency for a traditional slow sand filter. When compared to the previous field studies presented in Table 2.1, it can be seen that the removal efficiency was within the expected range of bacteriological removal efficiency for the BioSand Filter. In particular, the filter efficiency indicated in this study is greater than the efficiency of 80% reported in the original evaluation of the 1999 filters done by the researchers from UofC. This is likely due to the fact that the 1999 evaluation was performed while the biological layer was still ripening in the test filters. When compared to the other studies in the table, the indication is that, provided that the filter is kept in working condition and used daily, the BioSand Filter will continue to operate with the expected filter efficiency of a new (ripened) filter, even up to 8 years after filter installation.

2.3.1.2   Determinants of Filter Efficiency

The LR values of the filters were found to have a statistically significant linear correlation to the magnitude of source contamination, where higher removal efficiency is achieved at greater source contamination. The regression coefficients and statistical significance of the interdependent relationships between the logarithm of the source contamination metrics and the LR of each metric is displayed in Table 2.2.

Table 2.2   Regression Coefficients and Statistical Significance for Log Reduction vs. Source Contamination

N=24	LR Total Coliform			LR *E. Coli*			LR Turbidity		
	β	R^2	p	β	R^2	p	β	R^2	p
Source Coliform (Log_{10})	1.18	0.59	$p < 0.01$	0.83	0.49	$p < 0.01$	0.53	0.34	$p < 0.01$
Source *E. coli* (Log_{10})	0.47	0.18	$p < 0.05$	0.56	0.42	$p < 0.01$	0.26	0.16	$p = 0.057$
Source Turbidity (Log_{10})	1.49	0.40	$p < 0.01$	0.95	0.27	$p < 0.01$	1.07	0.58	$p < 0.01$

Hendricks and Bellamy (1991) describe a linear relationship between the magnitudes of the influent and effluent concentrations of heterotrophic bacteria in a traditional slow sand filter. The

data from this study was used to develop a similar model for the BioSand Filter, to predict the relationship between the source water quality (S) and filtered water quality (F), as follows:

$$\frac{F_2}{F_1} = \left(\frac{S_2}{S_1}\right)^{1-\beta}$$

(3)

This model predicts that a change in the filtered metric of any contaminant (F_2/F_1) as a result of an increase in a source metric by (S_2/S_1) will be less by a power of ($1 - \beta$). In particular, as β approaches 1.0, the filtered metric is completely unaffected by any increase in the source concentration. The values for β are theoretically different for every filter, but can be estimated as the slope of the regression line of LR versus the log of the source concentration. These are the regression coefficients presented in Table 2.2. The average value computed for β is 0.82 (SD = 0.39) and the average value of ($1 - \beta$) is 0.18. Using this model, an event that causes a ten-fold increase in source water contamination can be predicted to result in an increase of the filtered water concentrations by a factor of $10^{0.18}$ or approximately 1.5, and a 100-fold increase in source contamination will result in an increase by a factor of only 2.3. This is of important consideration from a human health and policy perspective because it can be used to predict the human health outcome of changes in source contamination as a result of events such as flooding in communities that use the filters for drinking water.

The peak flow-through rate through the filter was found to have a negative effect on the LR of total coliform $R^2 = 0.45$, $p < 0.01$, *E. coli* $R^2 = 0.31$, $p < 0.01$ and turbidity $R^2 = 0.28$, $p < 0.01$. This is to be expected as, according to Darcy's Law, the flow rate is proportional to the permeability of the filter media, which is in turn proportional to the effective pore size. The slower the observed flow, the smaller the effective pore size, and the greater proportion of contaminants are removed through filtration. The relationship between the normalized flow-

through rate and LR is included in Figure 2.4. One outlier data point was excluded from the

correlation.
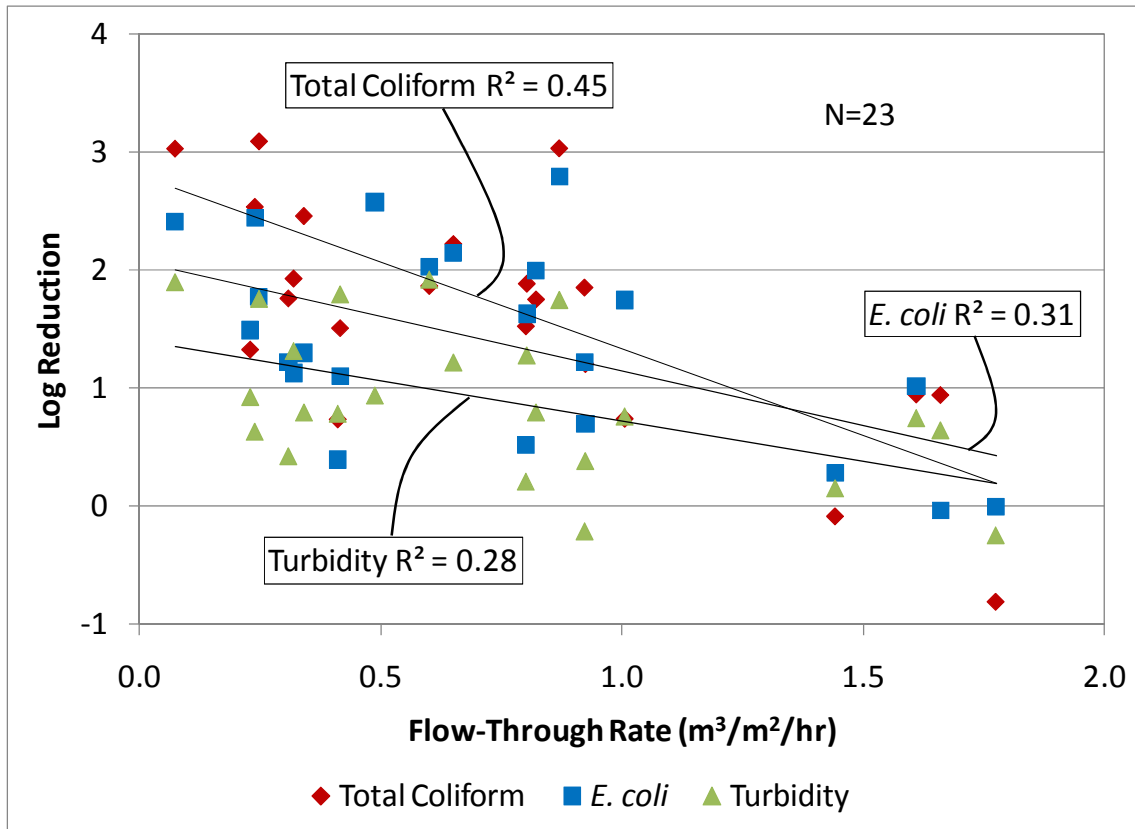
Figure 2.4   Log Reduction vs. Flow Rate

On March 15, 2007 CAWST released a technical update wherein they revised the

recommended maximum flow rate through the filter to be 0.6 L/min (CAWST, 2007) which

corresponds to a flow-through rate of approximately 0.6 m^3/m^2/hour for their particular design of

the BioSand Filter. The data from this study supports this new recommendation because, as can

be seen in Figure 2.4, the lower range of LR values begins to fall well below 0.5 and even into

negative values at flow rates above this recommended maximum. Furthermore, the mean LR of

total coliforms for those filters with a flow-through rate less than 0.6 m^3/m^2/hour was 2.2 (SD =

0.93), and the corresponding LR for those filters with greater flow-through rates was 1.3 (SD =

1.0), and this difference was found to be statistically significant at the $\alpha = 0.05$ level.

It has been demonstrated in laboratory studies that the flow rate through the BioSand Filter decreases over time as the biological layer develops (Buzunis, 1995; Stauber et al., 2006). As a result, the time period since the last harrowing of the biological layer can be considered a determinant of the flow rate, and regulating the frequency of maintenance is one method for filter users to achieve this recommended maximum flow rate. Unfortunately, much confusion was observed among the filter users in Posoltega regarding filter maintenance. The users were divided almost equally between those that washed their filter when the "flow is slow", when the "top of the filter appeared dirty", and on a "regular schedule". The reported maintenance frequency varied from every second day to once per six months, with an average of 39 days (SD = 36 days). This suggests that there would be benefit in training filter users with a more clearly defined recommended maintenance frequency. While the optimum maintenance frequency for a particular filter is dependent upon many factors including source contamination and daily use, the data suggests that there is no detriment to filter efficiency in allowing six months between washing cycles. Instructing filter users to wash their filter no more than once per six months, except when the flow rate is so slow that it no longer meets the family's needs, is one solution to resolve this confusion.

The standing depth of water over the top of the sand during the pause period was also found to have an effect on the LR of total coliforms $R^2 = 0.35$, $p < 0.01$ and *E. coli* $R^2 = 0.49$, $p < 0.01$. This is contrary to the findings of Buzunis (1995) based on analysis of oxygen transfer through the depth of water to the biological layer during the pause period. One possible explanation for this discrepancy is that a greater depth of water means there is less disturbance to the biological layer at the top grains of sand when the source water is poured into the filter, even with the diffuser plate in place. This would suggest that the need to keep the biological layer as undisturbed as possible during filtration is of greater consideration for filter efficiency than the transfer of oxygen to the biological layer or the depth of filter media in the filter.
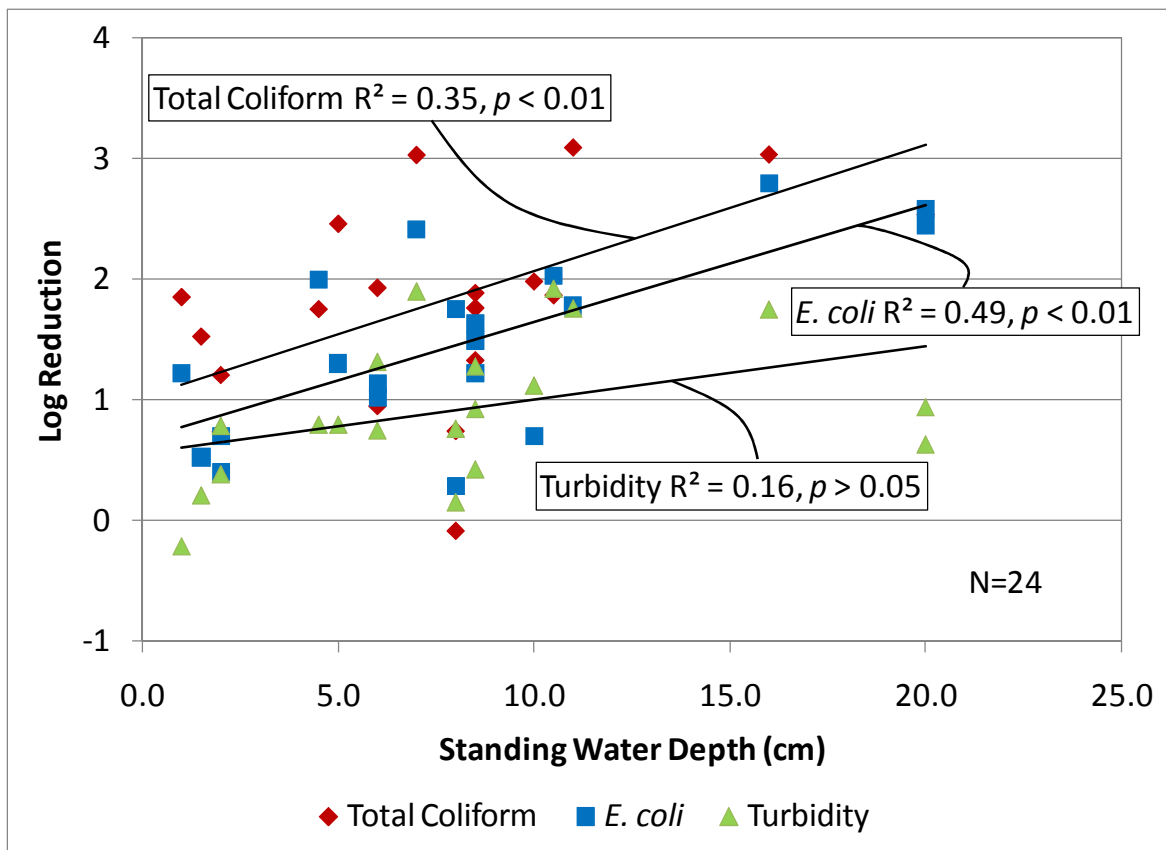
Figure 2.5   Log Reduction vs. Standing Water Depth

The current BioSand Filter designs call for approximately 50 cm of sand as filter media in the vertical column and 5 cm of standing water over the top of the sand. Further investigation is required to determine if these parameters can be changed to achieve higher filtration efficiency, or if there are other changes that could be made to the design of the BioSand Filter to reduce the disturbance to the biological layer. Even changing the location of the diffuser plate so that it sits submerged during the pause period would cause more energy to be absorbed in the water above the diffuser plate and keep the turbulence away from the biological layer when pouring in a bucket of source water.

No statistically significant relationship was detected between the filter efficiency and the daily filter loading rate. The shared filters that were being used to filter up to six buckets (120 L) per day were achieving the same log removal as those that were used to filter only one bucket per day. This suggests that there is no negative impact as a result of sharing a BioSand Filter

between families and filtering multiple buckets of water to meet the needs of all the families. This practice can be promoted in instances when one family's filter is broken or is simply not in use during the period after maintenance when the biological layer is still ripening.

No statistically significant differences in filter efficiency were detected between filters of different construction materials of plastic or concrete, between filters installed in different years or between filters installed in different communities. That the filter efficiency does not depend upon the construction materials is to be expected as the structural component is nothing more than a container for the filter media, and only needs to be structurally sound in order for the filter to work. That no difference in filter efficiency was detected between filters of different ages provides further evidence that the long term filter efficiency can be expected to remain constant, and this is independent of the community where the filters are being used.

2.3.2 Sustained Use of the BioSand Filter

Of the 234 BioSand Filters installed in Posoltega between 1999 and 2004, only 24 were still found to be in operation, representing a rate of sustained use of only 10%. The distribution of filters found to be in use is displayed in Table 2.3. The separate rates of sustained use for the 1999 filters and 2004 filters are 30% and 7% respectively. The remaining filters were found to be in various states of disuse and disrepair: cracked, leaking, broken, dismantled, emptied or otherwise abandoned and unused. The principal cause for disuse was structural failure in the concrete filter walls, particularly for the 2004 filters.

Table 2.3   **Summary of Sustained Use of the BioSand Filter**

Installation Year	BioSand Filters Installed		BioSand Filters in Use as of 2007	
	1999	2004*	1999	2004
El Trianón	34	20	10	5
San Gilberto		50		1
Posolteguilla		50		2
Buenos Aires		10		3
El Mojón		50		3
San Agustín		20		0
Total	34	200	10	14

* Distribution of 200 filters from 2004 estimated according to R. Hernández, MINSA Posoltega (personal communication, January 22, 2007)

2.3.2.1   Failure Mechanisms of 1999 Filters

Of the 34 filters from 1999, all installed in El Trianón and the surrounding hamlets of Corcovado and Monte Verde, only 10 were found to still be in operation. Of the others, 14 were broken, 7 were abandoned, and 3 were in functional condition, but were not actually in use (e.g. locked away inside the school's storage room). The failure mechanism of the broken filters was typified by cracks developing in the structural body of the concrete filters, and the outlet pipe becoming dislodged from the plastic filters.

Reportedly, many of the broken 1999 filters occurred as a result of families trying to move them as part of the community relocation after Hurricane Mitch. The original location of El Trianón was adjacent to a river that experienced significant flooding during Hurricane Mitch in 1998; subsequent to this the entire community relocated 500 m to the north away from the river. While the relocation was still underway, some families received filters at their homes in the original community location. When these families moved to their new homes, many of the filters were damaged during the transition. Other filters were abandoned altogether at the old homes when the family moved to their new homes or away from El Trianón completely.

The implementation of the 2004 filters and their subsequent failure was another indirect cause for failure of some the 1999 filters. In some cases the families in El Trianón that received a second filter in 2004 disassembled their otherwise operational 1999 filter; when the 2004 filter failed the family was left without any operational filter to use.

2.3.2.2   Failure mechanisms of 2004 filters

With respect to the 2004 filters, by far the most common reason identified for filter failure was significant cracking in the concrete walls causing the water to leak out of the filter. A leak in the filter below the sand level will cause the water to drain down away leaving the upper reaches of sand dry and preventing the proper development of a biological layer. There is also the inconvenience caused to the user of having leaking water running along the ground, or where the filter is inside the home, pooling on the floor every time they wish to filter water. With the exception of a few cases where a leaky filter was still used regularly by the owner and thereby at least realizing the benefit of the filtration of the water through the sand media, the leak in the structure prompted the user to stop using the filter altogether, and to resume drinking water directly from the well.

The actual cause of the high incidence of cracking of the 2004 filters is not known with certainty. Anecdotal evidence suggests that the concrete was not given sufficient curing time to achieve any significant strength and durability. Every individual interviewed regarding the filter construction activities indicated that filters were removed from their molds after one day of curing and almost immediately loaded onto carts to be transported across rural dirt roads to the communities. In addition, many people from the community of San Gilberto made reference to "*el golpe*" ("the impact") which further suggests a callous unloading procedure upon arrival at the destination household with the relatively uncured concrete filter.

The difference in the long term durability between the 1999 and 2004 filters is likely a reflection of the fact that the 2004 filters were built by community members under the direction

of the NGO technicians at the health center where quality control would be more difficult to maintain than in a dedicated facility in Managua. This demonstrates the importance of maintaining strict quality control during filter construction to achieve a successful BioSand Filter implementation program.

2.4   Conclusions

This paper presents an evaluation of the BioSand Filters that were installed in Posoltega, Nicaragua in 1999 and 2004. This is an evaluation of the in-situ technology, determining the contaminant removal efficiency in operational filters, and identifying the failure mechanisms in failed filters. A more thorough discussion of the BioSand Filter as an intervention for the provision of drinking water for the communities of Posoltega can be found in Chapter 4.

Of the filters that are still working, it was found that filters were able to provide a 98% reduction in total coliforms, a 96% reduction in *E. coli* and 88% reduction in turbidity. These are consistent with other field evaluations of the BioSand Filter and suggest that there is no long-term decrease in filter performance provided that the filter is kept in working order and used every day. The filters will not deliver clean water in isolation of consideration of source water quality and/or additional treatment involving disinfection.

The log removal of the filter was found to have a statistically significant correlation with the logarithm of the source water contamination. This relationship can be used to predict the increase in filtered water concentrations as a result of an increase in source contamination. It is theorized that the increase in a metric of filtered water will be less than an increase in a metric of source water by a power of 0.18. This type of predictive model can be used by health and policy decision makers in determining human health outcomes under different environmental scenarios, and help them make decisions as to the appropriateness of this technology for their community.

The log removal was found to have a statistically significant negative correlation to the flow rate through the filter, an expected outcome. Furthermore, the evidence from this paper supports

the new recommendation from CAWST on reducing the maximum flow rate through the filter to 0.6 L/min.

The log removal was found to have a statistically significant correlation to the standing depth of water above the sand during the pause period. This was an unexpected outcome and is contrary to the theories presented by Buzunis (1995) and others. Further investigation is recommended in determining the statistical significance of this relationship with a larger sample size drawn from available data from other field studies. It is recommended that the BioSand Filter design be revisited to reflect the outcome of the investigation of the relationship between filter efficiency and standing water depth, and to identify means to reduce the disturbance to the biological layer when pouring water into the filter.

No statistically significant correlation was identified between filter efficiency and the total daily loading of the filter. This suggests that there are no negative impacts of multiple families sharing a single BioSand Filter for their drinking water, and that this practice can be promoted as a human health policy when one family's filter is broken or simply down for maintenance during the period when the biological layer is still ripening.

Of the 234 BioSand Filters installed during the 1999 and 2004 implementation programs, only 24 filters were found to still be in operation which represents a rate of sustained use of only 10%. The most significant cause of failure in the filters was cracking in the concrete structure. In order for implementation of the BioSand Filter to be successful, strict quality control must be maintained during filter construction, particularly in the curing of the concrete.

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3 EVALUATION OF FIELD TESTING TECHNIQUES USED IN A HOUSEHOLD WATER TREATMENT STUDY IN POSOLTEGA, NICARAGUA

3.1 Introduction

Undertaking microbial water quality testing in rural and remote areas of developing countries requires consideration of the setting in which the testing will be conducted. This can include limited access to laboratory facilities and supplies such as consumable materials, sterile equipment and distilled water, as well as financial constraints and a finite quantity of consumable materials that can be transported, all of which limit the number of tests that can be performed. Nonetheless, the ability to produce reliable and accurate water quality data in this setting is important as the people in these areas are often at the greatest risk of waterborne illnesses, and identifying the water quality parameters associated with these illnesses is one of the first steps in determining the health risks (World Health Organization [WHO], 2006). A case study illustrating this scenario is presented here.

The BioSand Filter is a form of household water treatment technology based on slow-sand filtration at a scale that is appropriate for a single household (Manz et al., 1993; Buzunis, 1995). Laboratory tests have demonstrated that the BioSand Filter is capable of removing 97% of fecal coliforms and achieving 4 log-reduction of *Giardia* cysts and *Cryptosporidium* oocysts, and have been shown to remove 50 to 90% of organic and inorganic toxicants (Palmateer et al., 1999). A schematic of the BioSand Filter is shown (Figure 3.1). Thirty-four BioSand Filters were introduced into the remote community of El Trianón, Nicaragua, in 1999 as an emergency aid to provide clean drinking water to families impacted by Hurricane Mitch (Baughen et al., 1999). In

2004 the program was expanded to install 200 more filters across six rural communities in Posoltega. Families in this agricultural area typically rely on individual hand-dug shallow wells for their source water; previous studies have shown these wells to be contaminated with enteric pathogens and pesticides (*Centro para la Investigacion en Recursos Acuaticos de Nicaragua*, 1999a; b).
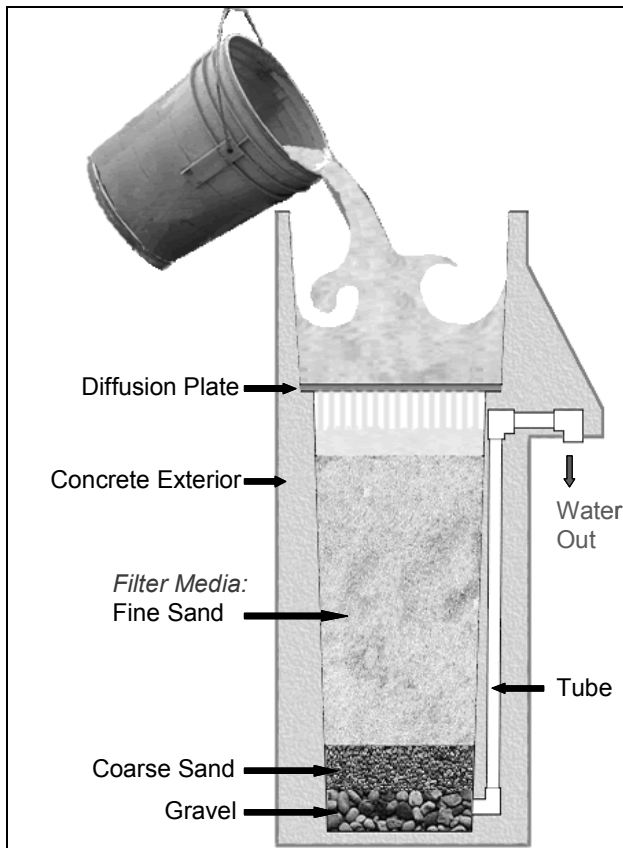
Figure 3.1   Schematic of the BioSand Filter. Source: Clean Water for Haiti (2003).

A field study was conducted from January to April 2007 to evaluate the BioSand Filters installed in Posoltega, Nicaragua. The objectives of the study were as follows:

- Characterization of the physical condition and operation of the BioSand Filters 8 years and 3 years after installation (i.e. post-1999 and 2004 respectively);
- Determination of the microbial and turbidity removal efficiency of those BioSand Filters still in operation;
- Evaluation of the BioSand Filter as an intervention for the protection of human health within the rural communities of Posoltega, Nicaragua.

This Chapter presents an evaluation of the fieldwater quality testing methods used to produce the microbial removal efficiency results for evaluating the BioSand Filter. A discussion of the efficacy of the BioSand Filter is presented in Chapter 2, and a thorough discussion of the BioSand Filter as an intervention for the provision of drinking water for the communities of Posoltega is presented in Chapter 4.

The majority of the previous field studies of the BioSand Filter have used fecal coliforms as the metric with which to evaluate the microbial removal efficiency. Fecal coliforms are detected and enumerated following Standard Method 9222D: Fecal Coliform Membrane Filter Procedure (American Public Health Association [APHA], 1998), using m-FC agar to cultivate the indicator organisms and incubating at 45.5°C for 24 hours. Reported removal rates ranged from 80% (Baughen et al., 1999) to 99% (Manz et al., 1993).

The World Health Organization now recommends the use of *Escherichia coli* (*E. coli*) as an indicator organism for the possible presence of pathogens derived from human or animal feces, and states that *E. coli* "should not be present in drinking-water" (WHO, 2006). Unlike fecal coliforms, there is no universally prescribed methodology to detect and quantify the concentration of *E. coli* in drinking water sources. Various companies have developed proprietary techniques, agars and broths to assist in the isolation, cultivation and enumeration of *E. coli*. Recent BioSand Filter studies have applied some of these techniques and technologies in order to evaluate the *E. coli* removal efficiency of the filter. These include Most Probable Number (MPN) methods using IPEXX Colilert (Stauber et al., 2006) and membrane filtration techniques using growth media such as Difco modified m-TEC agar (Duke et al., 2006) and lauryl sulphate broth (Earwaker, 2006). These methods relied on collecting water samples and testing in a central facility and were reportedly successful in producing results within the constraints of each particular study.

The constraints faced in Posoltega included the remote locations of the communities where the BioSand Filters were installed and the lack of a convenient laboratory facility for processing water samples. The opportunities included in-kind contributions of a field water testing kit for performing field Membrane Filtration (MF) by the Center for Affordable Water and Sanitation Technology (CAWST) and access to a small work space including refrigeration, electrical power and daily access to hot-air sterilization by the Alma Nubia Lopez Health Center of Posoltega. The health center also provided the use of a motorized, three-wheeled rickshaw for transportation to the remote communities. Protocols were developed within the context of these constraints and opportunities in order to carry out field water quality testing, including the sterilization of field equipment, accurate measurement of sample volumes, production of sterile rinse water, incubation of the prepared membranes and enumeration of the results. Furthermore, the protocol was developed in order to accommodate and produce useful results across several orders of magnitude of microbial concentration.

The growth media selected for this study was m-coliBlue24™ (Hach, Loveland, CO). This growth media allows the simultaneous detection and enumeration of *E. coli* and total coliforms. Prepackaged in 2 ml ampoules, there is no requirement for media preparation and portioning, and no risk of contaminating the media. Previous evaluations of the m-coliBlue24 growth media have demonstrated its applicability for the detection of *E. coli* through presence/absence tests (Grant, 1997). The quantitative recovery of *E. coli* using m-coliBlue24 correlated well to the recovery of fecal coliforms using m-FC (Hamilton et al., 2005). It has also been demonstrated to be effective for the detection and enumeration of *E. coli* in food (Erdmann et al., 2002; Grant et al., 2006). A limitation of the m-coliBlue24 is that it must be stored between 2 and 8ºC, and thus access to refrigeration at the local health center was an important consideration in the choice of this medium.

In addition to the membrane filtration technique, SolarCult[TM] dipslides (Solar Biologicals, Ottawa, ON) were used to test the source water and post-filtered water for microbial presence. It was acknowledged that the SolarCult dipslides are intended as a visual reference for industrial use, and are not recommended for drinking water testing due to their high limit of detection. However, their simplicity in use and visual interpretation suggested that they may have a role in water quality testing that was worth investigating in remote locations where other resources are not available.

An evaluation of the field techniques used to undertake the microbial water quality testing was undertaken through a Quality Assurance / Quality Control (QA/QC) protocol in a controlled laboratory setting at the School for Environmental Health at the University of British Columbia. This was done to identify and quantify the sources of error associated with the techniques, and to gain a deeper understanding of the results produced in the field. The QA/QC consisted of preparing spiked solutions inoculated with known concentrations of indicator organisms, and applying the same water quality testing techniques used in the field with regard to both the membrane filtration and the dip-slide protocols.

3.2   Materials and Methods

3.2.1   Field Methods

The field methods included the identification of households where a BioSand Filter had been installed and was still in operation, acquiring consent from these households for their participation in the study, administering a questionnaire regarding water and sanitation practices around the home, and water quality testing.

At each household, samples for water quality testing were taken from the source water before it was introduced into the top of the BioSand Filter, from the filtered water immediately leaving the spout of the BioSand Filter, and from the storage container of filtered water currently being used as the family's source of drinking water. Each sample was tested for *E. coli* and total

coliforms using membrane filtration. In addition, the source water and stored water were tested for microbial contamination using the Solarcult dipslides.

3.2.1.1   Membrane Filtration

Membrane Filtration (MF) was used to test the water for coliform bacteria. The MF technique used was based on Standard Method 9222: Membrane Filter Technique for Members of the Coliform Group (APHA, 1998). The equipment used was the Potatest WE10005 (Wagtech International, Berkshire, UK). This equipment allows for the membrane filtration to take place in the field rather than transporting the water samples to a central laboratory facility. Field sterilization of the equipment was achieved with isopropyl alcohol wipes and through the combustion of methanol (Fisher Chemicals #A4524, Fisher Scientific, Pittsburg, PA) as per the Potatest operation manual (Wagtech, n.d.). A hand operated vacuum pump was used to draw water through a mixed cellulose ester membrane filter of pore size 0.45 µm (Fisherbrand #09-719-555, Fisher Scientific, Pittsburgh, PA). The membranes were then placed in sterilized aluminum Petri dishes (Wagtech #WAG-WE10406, Wagtech International, Berkshire, UK) on an absorbent pad (Millipore #AP10045S0, Millipore Corp, Billerica, MA) that had been saturated with 2 mL of m-coliBlue24 growth media. The differential media contains enzymes which cause coliforms to produce red colonies by their ability to reduce TTC (2,3,5-triphenyltetrazolium chloride), and *E. coli* to produce blue colonies by their ability to hydrolyze the enzyme substrate BCIG (5-bromo-4-chloro-3-indolyl-beta-D-glucuronide) to an insoluble salt, while suppressing the growth of non-coliform organisms (Hach Company, 1999).

In order to avoid making dilutions in the field, a variation from the Standard Method was the filtration of different volumes of test water where the anticipated number of organisms in 100 mL would be too high to produce evaluable results. Sample volumes of 1 and 10 mL were taken of the source water, and sample volumes of 10 and 100 mL were taken of the filtered and stored water. The 1 mL samples were measured using sterile, single-use plastic pipettes

(Fisherbrand #13-711-20, Fisher Scientific, Pittsburgh, PA), the 10 mL samples were measured using sterilized 10 mL Kimax beakers (Kimble #14000-10, Kimble Glass, Vineland, NJ) and the 100 mL samples were measured by filling the reservoir tube (funnel) on the membrane filtration equipment to an indicated mark. The measurement equipment was then flushed with sterile water. Of each water sample, the smaller volume was always filtered first to avoid unnecessarily repeating the flame sterilization; the number of any remaining organisms from the smaller volume would not affect the concentration of organisms of the larger volume.

The colonies on the membranes were incubated for 24 hours at 35±0.5 °C. The AC powered incubator included with the Potatest WE10005 equipment was kept at the health center where it was plugged into a standard 110V AC wall outlet (a transformer was used to convert to the 220V AC required for the equipment, and an accompanying rechargeable battery pack maintained power during the frequent power outages). The time period between placing the membrane into the Petri dish and placing the Petri dishes into the incubator was between 1 and 4 hours, allowing sufficient time for a recovery period for the microorganisms on the membrane. After the incubation period the colonies formed on the membrane were enumerated with the assistance of a 5x magnification handheld lens and a tally counter. A digital photograph was also taken of each series as part of record keeping.

Two "blank" samples were prepared every day to confirm the sterilization procedures, representing 11% of all of the samples taken. The sterile water used for rinsing and the preparation of "blank" samples was prepared nightly by boiling bottled water (Fuente Pura, Managua, Nicaragua) and allowing it to cool covered overnight. The rinse bottles themselves were sanitized using 70% rubbing alcohol solution purchased from a local pharmacy and allowed to air dry inverted overnight.

The 10 mL beakers and the aluminum Petri dishes were wrapped in aluminum foil and sterilized in a dry-air oven for 30 minutes at 300 ºC prior to use each sampling day. All of the waste materials from the MF procedures were incinerated at the Posoltega health center.

3.2.1.2   SolarCult Dipslides

Solarcult dipslides were used to test the source and stored water. The dipslides consist of a plastic paddle coated with growth media, attached to a handle/cap that fits a self-containing clear plastic vial. One side of the paddle was coated with nutrient agar to which TTC was added for the detection of heterotrophic bacteria and the other side was treated with MacConkey Agar for the detection of Gram-negative organisms (Solar Biologicals, 2006).

The paddle was dipped into the water sample for three seconds and returned to the vial, closing the cap sufficiently to prevent contamination but allowing air exchange. The vials were incubated at room temperature which ranged between 25 and 30°C. After approximately 48 hours, the colonies formed on either side of the dipslide were enumerated. A visual aid was provided with the product to allow for an order-of-magnitude approximation of the organism concentration; however for the purposes of this study the colony counts were recorded and used for analysis.

The dipslides were disposed of by filling each vial with household bleach, sealing the cap and incinerating them at the Posoltega health center.

3.2.2   Laboratory Methods

In order to provide a level of confidence in the results produced in the field, a quality assurance / quality control (QA/QC) procedure was undertaken in a controlled laboratory setting at the School of Environmental Health at the University of British Columbia. The specific objectives of the QA/QC work were to identify and estimate the sources of error associated with the methodology used in the field. This included determining the correlation of the MF results to the expected organism concentration. The errors associated with volume measurements and with

enumerating colonies from samples tested at the same volume and across different volumes were also quantified. In addition, colonies growing on the m-coliBlue24 media were isolated and identified for confirmation of the differential count.

3.2.2.1 Preparation of Test Solutions

The QA/QC work was based on prepared solutions inoculated with a known concentration of indicator organisms. From the preliminary results from the field water quality testing, the prepared test solutions needed to cover a range from approximately 10 to 1,000 Colony Forming Units (CFU)/100 mL for *E. coli*, and 1,000 to 100,000 CFU/100 mL of total coliforms. For the purpose of the laboratory work, *E. coli* (ATCC #25922) and *Salmonella enterica* (ATCC #29058) were chosen as representative of faecal contaminants of water. A third organism, *Enterococcus faecalis* (ATCC #29212), was included in the prepared solutions to mimic a background organism suppressed by the m-coliBlue24 as well as on the dipslide MacConkey agar, but would be detected by the TTC on the reverse of the dipslide. The *E. faecalis* was inoculated into the solution at a concentration several orders of magnitude greater than that of the other two organisms such that if the suppression of its growth failed, the non-coliform background would be readily detected.

The test solutions were prepared by first inoculating a neat suspension with colonies from an agar plate streaked with the desired organism until the optical density (OD_{360}) measured with Ultrospec II (LKB Biochrom, Cambridge, UK) was between 0.5 and 1.5, corresponding to a range of 10^8 to 10^9 bacteria per mL. Serial ten-fold dilutions were performed from the neat suspension as described in Standard Method 9215: Heterotrophic Plate Count (APHA, 1998), and three aliquots of 0.1 mL of the fifth dilution were dispersed and spread onto Tryptic Soy Agar (TSA) (Difco^{TM}, Becton, Dickenson and Company, Sparks, MD). The average count from these three plates was used to predict the concentration of the neat sample suspension, and hence the number of organisms in the final concentration of the spiked test solution. For the purpose of

this study the outcome of this method was considered to be the "true" spiked concentration of the test solution.

Nine test solutions were prepared and tested by MF a total of nine times: three times each for the sample volumes of 1 mL, 10 mL and 100 mL. Each solution was also tested with three dipslides. The water quality testing techniques used were identical to the field methods, including the use of the Potatest equipment for the MF procedure and incubating the membranes, the preparation of the sterile rinse water and the application of the dipslides.

3.2.2.2   Volumetric Measurement

The specific volumes of 1 mL, 10 mL and 100 mL as measured in the field were confirmed by gravimetric analysis using top loading balances (Sartorius, Mississauga, ON). Five randomly selected 1 mL pipettes and all eleven 10 mL Kimax beakers used in the study were tested five times each by filling to the indicated mark and recording the mass of the collected water sample. The 100 mL reservoir tube on the membrane filtration equipment was similarly tested a total of eight times, with a new membrane filter in place for each test.

3.2.2.3   Colony Identification

An external water source (duck pond at Jericho Beach in Vancouver, BC) was tested using the MF technique with the m-coliBlue24 growth media. Six blue colonies (suspect *E. coli*) were subcultured onto Eosin Methylene Blue (BBL^TM, Becton, Dickinson and Company, Sparks, MD) agar and five red colonies (suspect coliform) were subcultured onto TSA, repeating as required until pure cultures were obtained. Suspensions were then prepared of each culture, and API 20E test strips (bioMérieux, St. Laurent, Quebec) and the corresponding online application APIWEB^TM (bioMérieux, St. Laurent, Quebec) were used to identify the cultures as per the included directions.

3.2.3 Statistical Methods

The coefficient of variation was used to quantify the error associated with the individual procedures, and Student's t-tests (two-tailed heteroscedastic) were used to determine the statistical significance of the difference between data sets, or the statistical significance of a correlation between variables. The coefficient of variation is the normalization of the standard deviation by the mean and is therefore an appropriate measure of the error because both the organism concentration and the actual filtered volume varied across multiple orders of magnitude.

3.3 Results

3.3.1 Laboratory Results

The results of the MF technique were compared to the predicted spiked organism concentration for *E. coli* and *Salmonella*, and the ratio between the concentrations was calculated (Table 3.1).

Table 3.1   Comparison of MF Results to Spiked Concentrations

Sample Number			1	2	3	4	5	6	7	8	9
E. coli		Spiked Concentration	**12**	**-**	**79**	**-**	**950**	**160**	**97**	**580**	**480**
	MF Results*	1ml Mean Result	ND	-	ND	-	500	200	ND	100	ND
		10ml Mean Result	10	-	80	-	280	30	10	30	90
		100ml Mean Result	5	-	80	-	333	57	16	224	118
	MF Concentration**		**5**	**-**	**80**	**-**	**280**	**57**	**16**	**224**	**118**
	Ratio of MF to Spiked Conc.		0.42:1	-	1.0:1	-	0.30:1	0.36:1	0.16:1	0.39:1	0.25:1
Salmonella		Spiked Concentration	**-**	**1700**	**-**	**16000**	**-**	**1400**	**18000**	**1400**	**13000**
	MF Results*	1ml Mean Result	-	500	-	15900	-	700	3000	200	4400
		10ml Mean Result	-	730	-	12600	-	410	3560	80	6020
		100ml Mean Result	-	676	-	TNTC	-	652	TNTC	289	TNTC
	MF Concentration**		**-**	**730**	**-**	**15900**	**-**	**410**	**3000**	**289**	**4400**
	Ratio of MF to Spiked Conc.		-	0.42:1	-	1.0:1	-	0.30:1	0.17:1	0.21:1	0.34:1

* The average of the three plate counts from each sample volume is reported in CFU/100mL. (ND = not detected; TNTC = too numerous to count)

** The MF Concentration was computed from the single plate count between 15 and 150 CFU where possible, or the otherwise nearest and most appropriate to minimize random error, as suggested in Figure 3.7.

3.3.1.1   Correlation to Spiked Concentration

No statistically significant difference was detected between *E. coli* and *Salmonella* for the ratio of the MF results to the expected results, despite the fact that there were several orders of magnitude difference between the concentrations of these two organisms across the different test solutions. The ratio was found to vary between 0.16:1 and unity, with an average of 0.41:1 (SD = 0.28:1). The linear regression between the concentration predicted by the MF technique and the spiked concentration (Figure 3.2) is statistically significant at $\alpha = 0.01$ level.
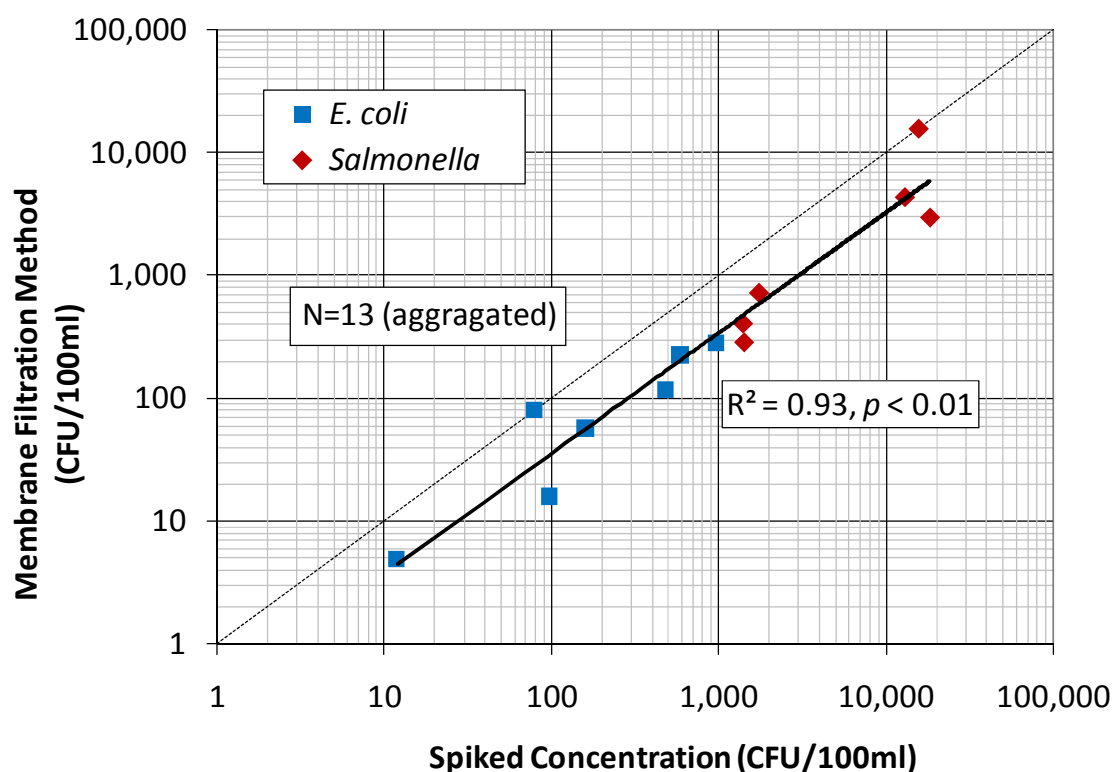
Figure 3.2 **Correlation of Membrane Filtration Results to Spiked Concentration**

3.3.1.2 Volumetric Variation

The field methods used to measure the 1 mL, 10 mL and 100 mL sample volumes were all

verified by repeating the procedures in the laboratory and measuring the mass of the sampled

water. The mean, coefficient of variation and statistical significance of the systematic bias were

then calculated (Table 3.2).

Table 3.2 **Gravimetric Analysis of Volume Measurements**

Nominal Volume (mL)	Mean Measured Mass. (g)	Coeff. of Var.	Systemic Bias	Statistical Significance
1	0.982	4.3%	-1.8%	$p < 0.05$
10	10.74	2.6%	+7.4%	$p < 0.01$
100	104.0	0.8%	+4.0%	$p < 0.01$

3.3.1.3   Coefficient of Variation

The coefficient of variation between the three individual plate counts from each filtered volume of each sample was computed. No statistically significant difference was detected between results for the type of organism (S*almonella* versus *E. coli*), nor for the sample volume. Because of the lack of effect, the data set was aggregated. The average coefficient of variation from the plate count was determined to be 38% (SD = 23%). Furthermore, a statistically significant negative correlation was detected between the coefficient of variation and the logarithm of the mean plate count at the $\alpha = 0.05$ level (Figure 3.3). The negative correlation is to be expected as the non-uniform distribution of organisms in a suspension results in greater random error at low concentrations and sample volumes, yielding higher variability between observations. It should be noted that this correlation does not apply at higher plate counts, where factors associated with the enumeration of significant numbers of colonies formed on the membrane contribute to the random error.
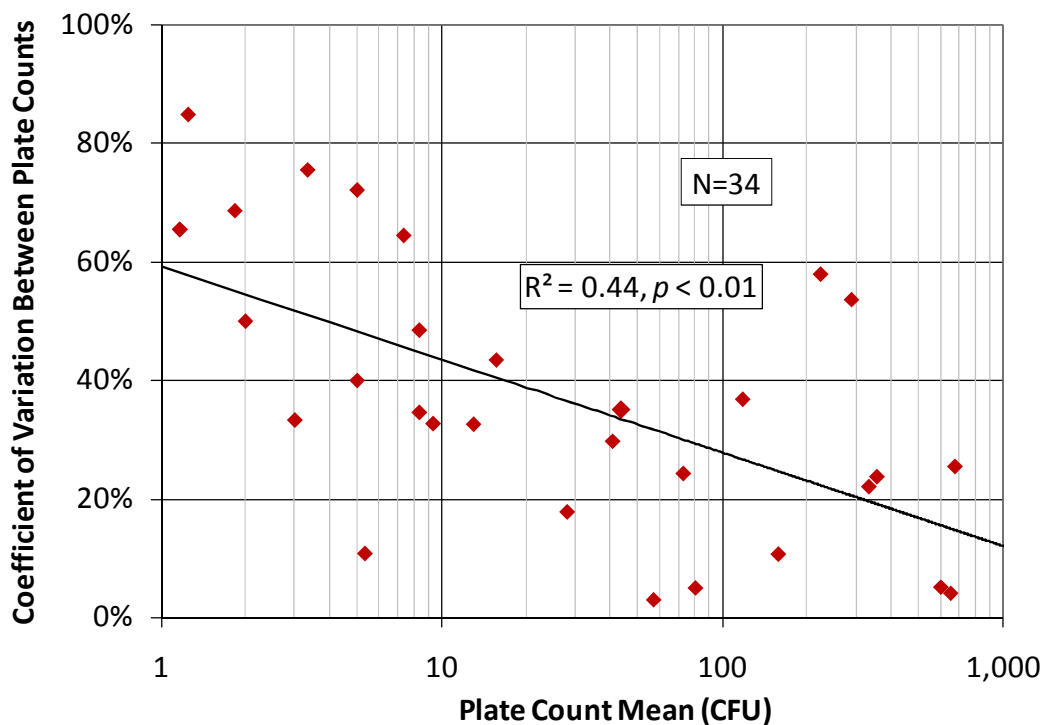
Figure 3.3   Coefficient of Variation vs. Plate Count

For each test solution and filtered volume, the triplicate plate counts were averaged and factored according to the filtered volume. A new coefficient of variation was then computed between the counts from the 1 mL and 10 mL samples, and again between the 10 mL and 100 mL samples. This was to mimic the field methodology, where each water sample was tested at either 1 mL and 10 mL volumes, or 10 mL and 100 mL volumes. Each computed coefficient of variation was treated as a separate observation.

No statistically significant difference was detected between the computed coefficient of variation between filtered volumes for the type of colony (*Salmonella* versus *E. coli*), nor between the results computed between the 1 mL and 10 mL volumes versus the 10 mL and 100 mL volumes. Because of the lack of effect, the data set was again aggregated. The average coefficient of variation computed across the different filtered volumes was 44% (SD = 31%).

3.3.1.4   Colony Identification

Of the six blue colonies suspected to be *E. coli*, five were successfully identified as such using the API 20E test strips and the corresponding APIWEB^{TM} online application. The sixth colony was identified as *Klebsiella pneumoniae spp pneumoniae* with 97.5% certainty. The incidence of false positives is reportedly 3% for *E. coli* (Grant, 1997).

Of the five red colonies suspected to be coliforms, three were identified as *Klebsiella oxytoca*, one as *Enterobacter cloacae* and one as *Raoultella ornithinolytica* (formerly classified as *Klebsiella ornithinolytica*). These are all Gram-negative, rod shaped bacteria (Bergey and Holt, 1994) which should rightfully be identified as members of the coliform group by the m-coliBlue24 growth media.

3.3.1.5   SolarCult Dipslides

The results from the SolarCult dipslides were compared to the spiked concentrations in the test solutions (Figure 3.4). The colony counts from the MacConkey side of the dipslide are plotted against the total spiked concentration of Gram-negative organisms in the test solutions

(*E. coli* and *Salmonella*) and the colony counts from the TTC side of the dip slide are plotted

against the total spiked concentration of microorganisms in solution (i.e. *E. faecalis*). The

regression line through both data sets is statistically significant at the $\alpha = 0.01$ level, although

this is dominated by the correlation between the higher TTC counts and the *E. faecalis*. The

lower limit of detection of the dipslides predicted by the regression line is approximately 1000

CFU/100 mL.
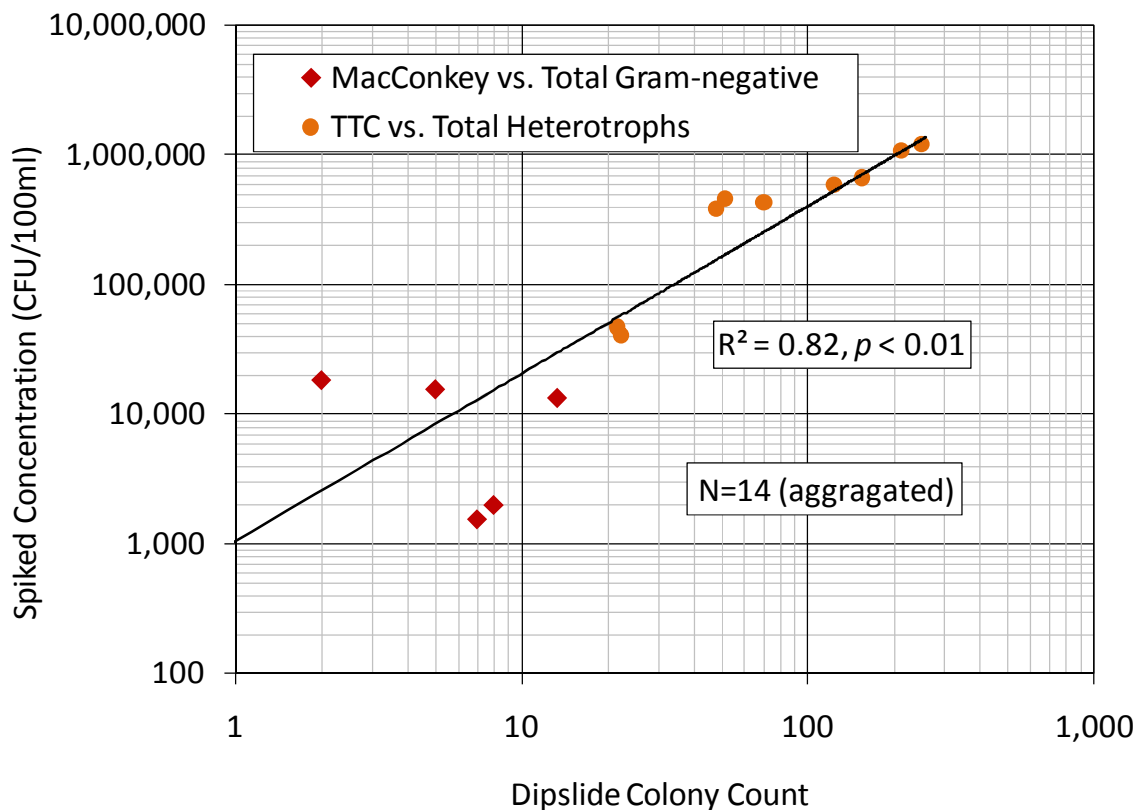
Figure 3.4   Correlation of Dipslide Colony Count to Spiked Concentration

3.3.2   Field Results

A total of 255 field samples were tested for both *E. coli* and total coliforms by MF with

m-coliBlue24 growth media; 92 of these were of source water, 85 of filtered water and 78 of

stored water. The results of the field testing (Figure 3.5) indicate that the BioSand Filters were

nearly achieving a $\log_{10}$ reduction of 2. Unfortunately, the stored post-filtered water was

approximately a full order of magnitude greater than the filtered water, suggesting problems with regrowth and recontamination. In general, neither the filtered water nor the stored water met the WHO guidelines for safe drinking water (WHO, 2006). A further discussion of the BioSand Filter evaluation can be found in Chapter 2.
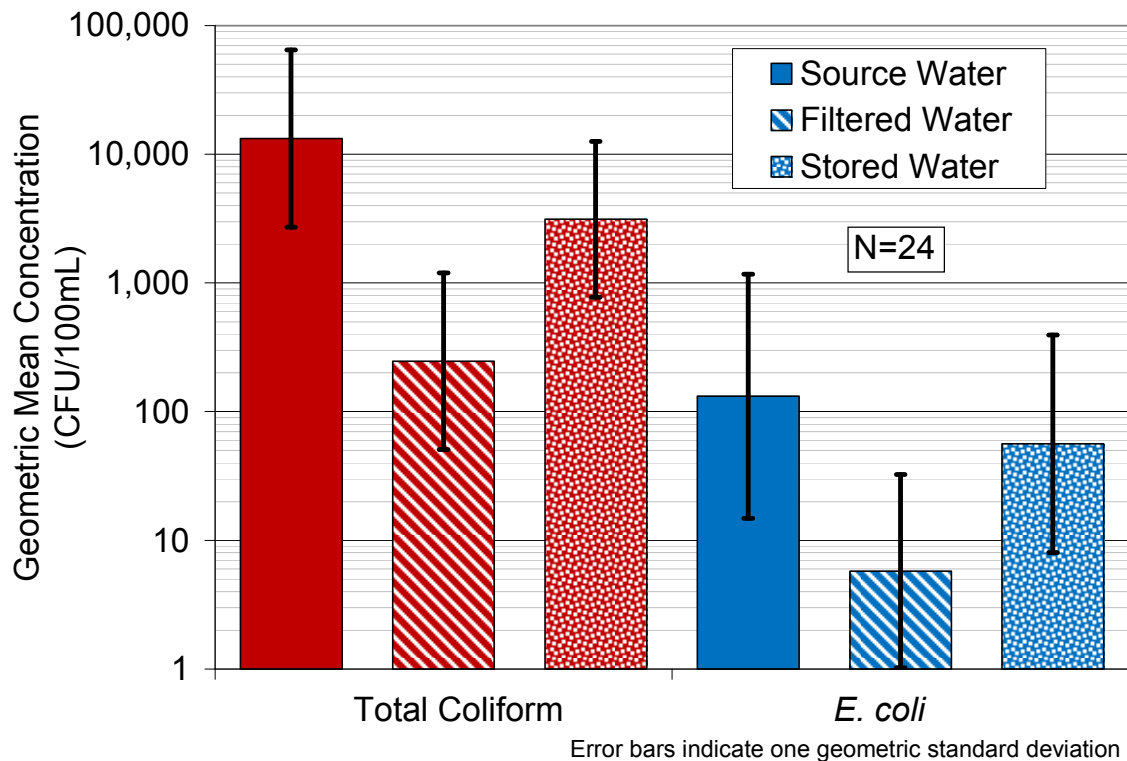
Figure 3.5   BioSand Filter Evaluation Microbial Results

3.3.2.1   Coefficient of Variation

The field methodology included testing duplicates of water samples at different volumes to cover a broad range of possible concentrations and to provide a level of confirmation of the results. Of these, there were 179 pairs of tests (358 results) where both the larger and smaller sample volumes yielded countable, useable results; 104 pairs for *E. coli* and 75 pairs for total coliforms. The average coefficient of variation computed between the results from the corresponding pairs of larger and smaller volumes was 51% (SD = 35%). No statistically

significant difference was detected between this coefficient of variation from the field data and the corresponding computation from the laboratory data.

3.3.2.2 SolarCult Dipslides

The results of the SolarCult dipslides from the field were compared to the membrane filtration results (Figure 3.6). The colony counts from the MacConkey agar side of the dipslide are plotted against the total coliform concentration (including *E. coli*) determined by MF of the corresponding water sample. The regression line through the data set is statistically significant at the $\alpha = 0.05$ level, and predicts the lower limit of detection of the dipslides to be between 1000 and 2000 CFU/100 mL. The scatter in the data is likely a result of the fact that the MacConkey agar can identify environmental non-coliform Gram-negative bacteria encountered in the field that are not detected by the m-coliBlue24 growth media. As a result, the dipslides may overestimate the concentration of total coliforms. This is further indicated in that the regression line from the laboratory data appears to form an approximate upper bound for the field data, representing the case where all Gram-negative organisms in a water sample detected by the MacConkey agar side of the dipslide are indeed coliforms detectable by the m-coliBlue24 growth media.
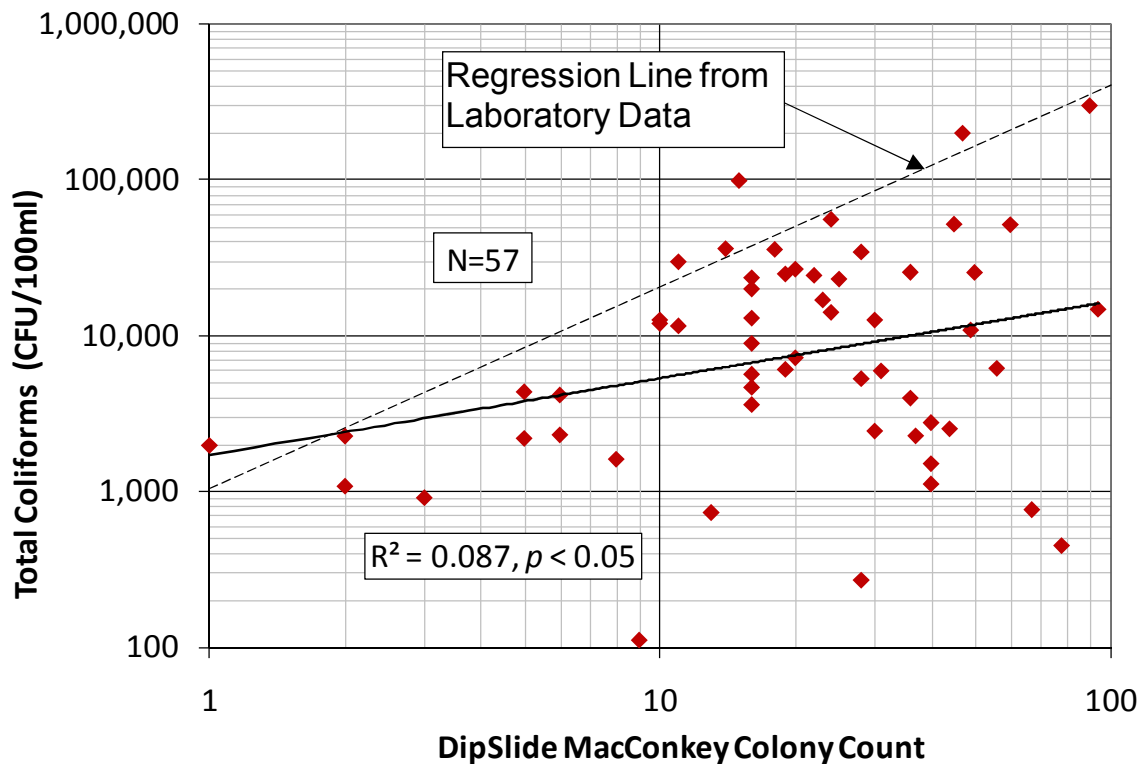
Figure 3.6   Correlation of MacConkey Agar Colony Counts to Field MF Results

3.4   Discussion

The water quality testing methods employed for this study were successful in yielding useful, reproducible numeric results within the context of the constraints and opportunities encountered in the field. In particular, the field membrane filtration using m-coliBlue24 allowed for the enumeration of *E. coli* and total coliforms up to concentrations of 100,000 CFU/100 mL in source water while maintaining a detection threshold of 1 CFU/100 mL in filtered water. The technique used to achieve this successfully addressed the issues related to limited access to laboratory facilities. The SolarCult dipslides exhibited limited correlation to the MF results in the field, and thus are likely not an appropriate tool for conducting field water quality testing as part of an evaluation of HWT technology. However, the detection limits and good correlation to laboratory results as well as the ease of use make them an appropriate tool for conducting

preliminary water quality testing in preparation for the implementation of a HWT project, and for engaging community members in the importance of safe water. The QA/QC procedures conducted in the laboratory provide a level of confidence in the field methods and the results thereby obtained.

3.4.1 Membrane Filtration Using m-coliBlue24

One of the most significant outcomes of the QA/QC work with regard to the m-coliBlue24 was the identification of the colonies formed from the arbitrary sample of duck pond water; five of the six blue colonies were successfully identified as *E. coli* and all of the red colonies were identified as species belonging to the coliform group using the independent method of the API 20E test strips. Coupled with the successful suppression of *E. faecalis* as a background organism, this outcome leads to a very high level of confidence that the organisms identified through the MF technique using the m-coliBlue24 are in fact the indicated type of organisms. The reported rate of false positives for m-coliBlue24 is 3% for *E. coli* and 27% for coliforms (Grant, 1997).

The results of the QA/QC suggest that the MF technique tends to underestimate the actual concentration. This may be due to a variety of factors, including organisms that are stressed or even killed on the membrane during the membrane filtration, or organisms clinging to the interior equipment walls in spite of the rinsing techniques. Nonetheless, the MF technique appeared to be accurate to an order-of-magnitude level of precision which was sufficient for the purposes of this study.

Specific to the field methodology and equipment used in this study, a bias of up to 7% was detected from the volumetric measurement techniques. While statistically significant, this bias is relatively small in comparison to the random error associated with individual plate counts or averaging the results derived from testing across different sample volumes, and therefore no correction was applied. The average coefficient of variation associated with any plate count was 38%. The average coefficient of variation associated with averaging across different sample

volumes was found to be 44% in the laboratory and 51% in the field; no statistically significant difference was detected between the laboratory and field data set, suggesting that the study results would not have had any less random error had the water samples been collected and transported to a controlled laboratory facility for testing.

One method of reducing the random error associated with the MF technique is to recognize that a greater coefficient of variation is typically expected at lower plate counts as a result of the more random dispersion of organisms in suspension at low concentrations. This can be observed by plotting a bounding curve on the plate count data (Figure 3.3), representing the maximum expected coefficient of variation at a given plate count. This curve is minimized at approximately 50 CFU with a maximum expected coefficient of variation of 50%. At plate counts below 15 CFU the non-uniform distribution of organisms in the test solution leads to greater random error associated with any measurement. When given the choice of computing a sample concentration from two plate counts from different volumes and the count from the smaller volume is below 15 CFU, it would be more prudent to only use the count from the larger volume (which should be less than 150 CFU) and thereby avoid factoring in the high expected error associated with the smaller plate count. At the other extreme, when the number of colonies are too numerous, other factors begin to affect the error associated with the plate count including the growth of overlapping and otherwise non-distinct colonies on the membrane, competition for nutrients in the growth media between colonies and from background microorganisms that prevent the formation of complete colonies, and human error associated with enumerating a high number of colonies.

To further this concept, the fact that there was no statistically significant effect from the filtered volume on this data set suggests that this bounding curve exists for each sample volume. The choice of how to compute the concentration of the test sample is then dependent on the plate count from each volume, where a plate count between 15 and 150 CFU is desired (Figure 3.7).

This concept is very similar to Standard Method 9222: Membrane Filter Technique for Members of the Coliform Group (APHA, 1998) which recommends targeting a plate count between 20 and 200 CFU. Some forehand knowledge of the approximate order of magnitude of microbial levels is required to know what sample volume to use for the MF; this is further compounded when both indicator organisms of *E. coli* and total coliforms are desired. The methodology used in this study, testing 1 mL and 10 mL for source water and 10 mL and 100 mL for filtered and stored water, was found to be appropriate for the conditions encountered in the field.
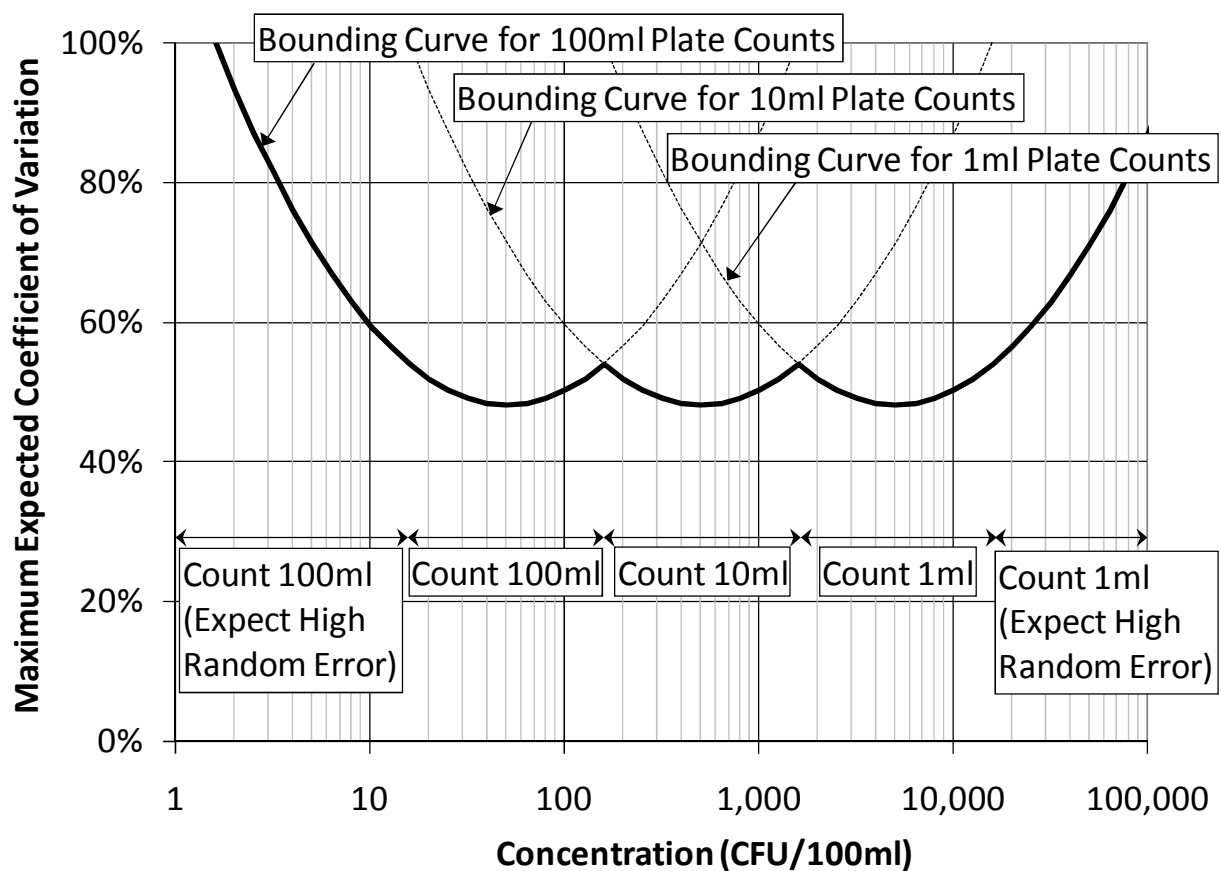
Figure 3.7   Minimization of Random Error in Membrane Filtration using Different Sample Volumes

A limitation of MF with m-coliBlue24 is the occurrence of growth on the membrane which can be difficult to interpret. Examples of this include smudging and/or dry patches on the membrane, growth around the perimeter of the membrane, colonies of non-uniform sizes and in

particular a "dusting" of tiny colonies across the membrane along with the standard-sized colonies growing on the membrane, colorless confluent growth across the membrane, and *E. coli* forming black rather than blue colonies. These types of results occurred in approximately 5% of the tests conducted. The smudging and perimeter growth can be controlled through careful techniques used in the field. The dusting of tiny colonies and the colorless confluent growth were replicated in the laboratory under circumstances where the number of *Salmonella* organisms was in excess of 10,000 and the background organism of *E. faecalis* was in excess of 400,000 CFU in the 100 mL test sample. For this reason it is important to have a trained individual interpret the MF results, to avoid the danger of misinterpreting colorless growth as an organism concentration of zero, rather than as truly being too numerous to count. It is suspected that temperature effects during the storage and transportation of the m-coliBlue24 may be related to the black *E. coli* colonies being formed instead of blue. A further investigation into the temperature effects on the growth media is required to further demonstrate the applicability of using m-coliBlue24 for field water testing in developing countries where maintaining the temperature between 2 and 8 ºC during storage and transportation may be difficult.

3.4.2 SolarCult Dipslides

The regression line plotted between the colony counts from the SolarCult dipslides and the spiked organism concentrations from the laboratory data (Figure 3.4) can be used as a calibration curve, much the same as the visual aid provided with the product. The advantage of the calibration curve is the increased precision over the visual aid within the countable range, up to approximately 100 colonies. The suggested relationship between *X*, the number of colonies counted on one side of the dipslide and *Y*, the concentration of the corresponding organism (measured in CFU/100 mL) is as follows, including the 95% confidence interval:

$$\log_{10} Y = (1.3 \pm 0.4) \cdot \log_{10} X + (3.0 \pm 0.6)$$

(4)

An understanding of the corresponding organisms being identified is required when interpreting the results from the dipslide. The counts on the TTC agar side of the SolarCult dipslide correspond to the concentration of total heterotrophic bacteria in the sample and the counts on the MacConkey agar side of the dipslide correspond to the concentration of Gram-negative organisms. The dipslide field data (Figure 3.6) indicates that the MacConkey agar colony count does not correlate directly to the concentration of total coliforms, as there may be environmental Gram-negative non-coliforms present in the water sample. The calibration curve used with the MacConkey agar side of the dipslide may therefore over-predict the actual concentration of total coliforms by as much as two orders of magnitude. It does however provide a good upper bound for the concentration of total coliforms and can therefore be used for preliminary field water quality testing in preparation of a HWT implementation program.

It is not recommended that the dipslides be used as a presence / absence test for the detection of *E. coli*; the high limit of detection of approximately 1000 CFU/100 mL leaves open the possibility for false negatives within the range of concentrations that can be hazardous to human health.

Within the context of the implementation of the BioSand Filter, there are two roles for which the SolarCult dipslide is particularly well suited. The first is that because the dipslide is a self-contained, easy-to-use method of water testing, with no additional equipment required for incubation (particularly in tropical climates there the ambient temperature is sufficient) it can be readily used by local health and sanitation representatives to provide an initial estimate as to the severity of microbial contamination of a raw water source. Furthermore, the outcome of the test can help in determining what type of intervention is required and the suitability of any particular HWT technology. In particular, any growth on the MacConkey side of the dipslide used to test the raw source water would provide an indication that the BioSand Filter should not be used in

isolation to provide clean drinking water, as it can reasonably only be expected to provide a log-reduction of around 2. In this case, the filtered water would still have greater than 10 CFU/100 mL of Gram-negative organisms and some form of additional treatment including disinfection would still be required.

The second role of the dipslides is as a visual aid for the local health and sanitation representatives to engage community members and promote safe water and hygiene practices within the community. The concept of microorganism presence in water and the connection to human health is often a difficult concept for lay persons to understand as it cannot be visualized. The dipslides can be used to visually demonstrate the severity of microbial contamination in water sources, and show the degree to which the water is improved through safe water practices, in a manner that is clearly understood.

A limitation of the SolarCult dipslide relates to the fact that it is not specifically intended for drinking water purposes, and as such has a high lower limit of detection. However, given the simplicity of use and interpretation of results, research into modifications of either the technology or the methodology is recommended for better adaptation to water quality testing in rural and remote parts of the world.

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4 FAILURE OF HOUSEHOLD WATER TREATMENT IN POSOLTEGA, NICARAGUA

4.1 Context

The World Health Organization (WHO) Guidelines for Drinking Water Quality recommends developing a Water Safety Plan (WSP) for ensuring the safety of drinking water supplies through the use of a system approach that encompasses all steps in water supply from catchment to consumer (WHO, 2006). The three key components of a WSP are system assessment, effective operational monitoring, and management. The most familiar context for the application of a WSP is in a community system with centralized treatment and piped distribution. In this framework the system is assessed for its ability to deliver safe water, operational monitoring is conducted to ensure that the operators have the capacity to use and maintain the technology and that the control measures are being implemented, and management systems are in place to provide the required resources.

A novel approach for the delivery of clean drinking water that has been forwarded by the WHO and other water, sanitation and health policy makers worldwide is Household Water Treatment (HWT), where a family takes responsibility for treating their own drinking water through the application of a household-based technology, and safely storing the treated water for subsequent consumption. Dr. Jamie Bartram, Coordinator for the Water, Sanitation and Health Programme of the WHO states that "there is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically reducing the risks of diarrheal disease and death. These household interventions are cost-effective, with an overall benefit of up to $60 US per $1 US invested" (Sobsey, 2002, foreword).

This paper presents an argument for the use of a holistic water system approach such as the WSP when implementing a HWT program, using the BioSand Filter implementation in Posoltega, Nicaragua as a case study. While HWT does not rely on the infrastructure required for centralized treatment and piped distribution, it is still a form of a community water system and therefore requires a system approach. The fundamental difference between a centralized system and HWT is that every user of the HWT technology is an operator, and as such needs the developed capacity and training to successfully use and maintain the technology. The assessment of the appropriateness of the technology, the operational monitoring and the management components of a WSP are all still required in order to execute a successful HWT implementation program.

4.1.1   Background

4.1.1.1   Municipality of Posoltega

The Municipality of Posoltega is located in northwestern Nicaragua, in the Department of Chinandega, bordering the Department of Leon. The municipal population is 17,000: 34% inhabit the urban town center and the rest live in rural communities dispersed across contiguous agricultural lands (*Instituto Nacional de Información de Desarrollo*, 2005). The urban town center and a small number of rural communities are serviced by community water distribution systems that rely on pumping, storage and disinfection. The other rural communities rely on shallow hand-dug wells for their drinking water. Water quality studies of the water from these wells by the Center for Water Resources Research (*Centro para la Investigación en Recursos Acuáticos*, CIRA) at the National Autonomous University of Nicaragua indicate that they are contaminated with enteric pathogens and pesticides (CIRA, 1999a; b).

Posoltega was hit particularly hard by Hurricane Mitch in 1998; heavy rains triggered a landslide from La Casita volcano which killed over two thousand people, and displaced thousands more. A joint project between CIRA, the University of Calgary (UofC) and an

international non-governmental organization (NGO) was initiated to bring clean water to those impacted by the hurricane. This project included delivering 34 BioSand Filters to impacted families in the rural community of El Trianón (Baughen et al., 1999). In 2004, this same NGO returned to Posoltega to deliver 200 more filters, replacing some of the filters in El Trianón and installing new filters in the rural communities of San Gilberto, Posolteguilla, Buenos Aires, El Mojón and San Agustín. A map of these communities is shown in Figure 4.1.
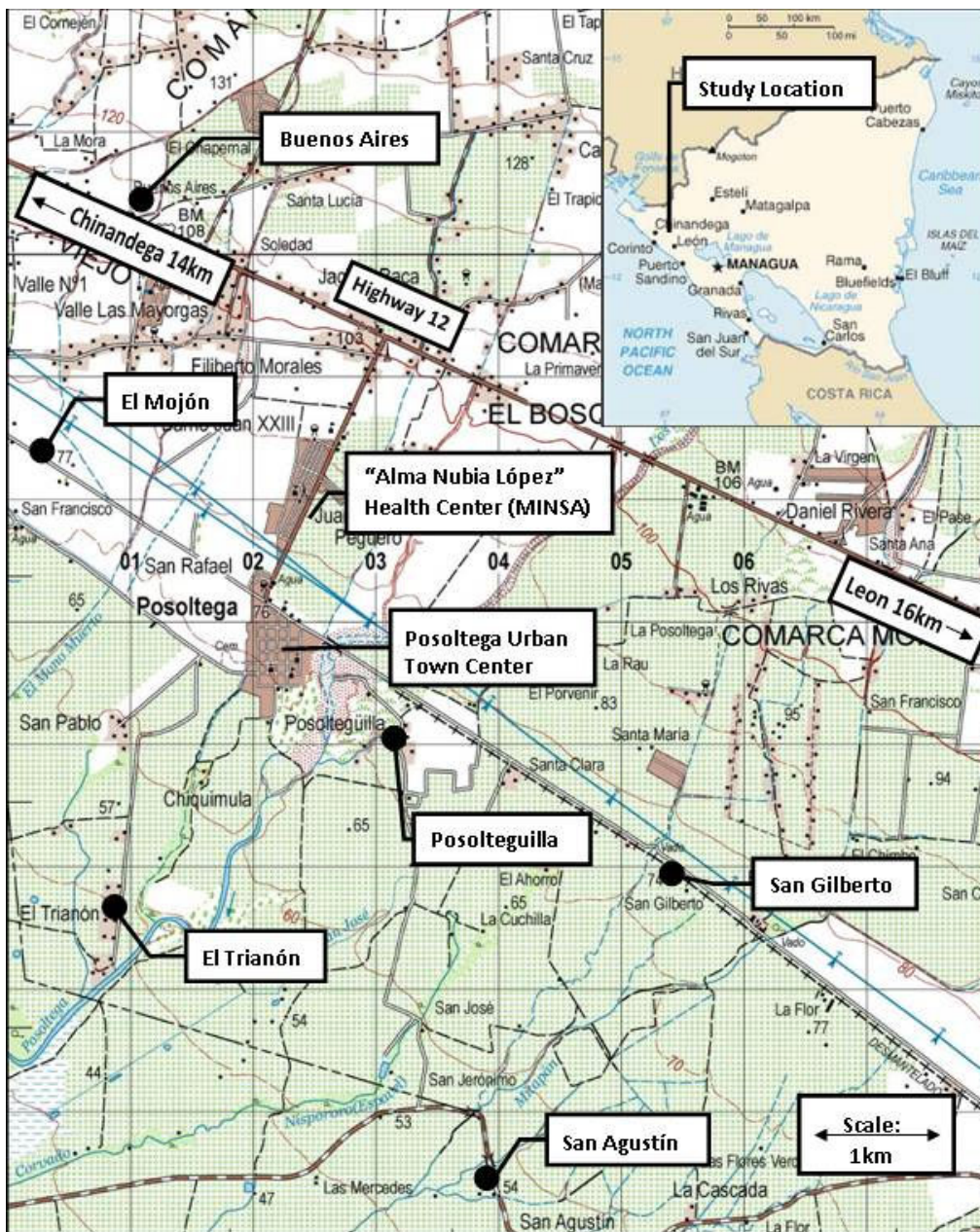
Figure 4.1   Map of Posoltega and Study Communities. Sources: US Dept of State (2007) and INETER (2006).

4.1.1.2   BioSand Filter

The BioSand Filter is a form of HWT that is based on slow-sand filtration at a scale that is appropriate for a single household (Manz et al., 1993; Buzunis, 1995). A schematic of the BioSand Filter is shown in Figure 4.2. Microbial inactivation occurs through natural die-off, predation and biological oxidation in the biological layer that develops at the top of the sand, and by filtration and adsorption through the sand media (Buzunis, 1995). Laboratory tests have demonstrated that the BioSand Filter is capable of removing 97% of fecal coliforms and achieving 4 log-reduction of *Giardia* cysts and *Cryptosporidium* oocysts, and can remove 50 to 90% of organic and inorganic toxicants (Palmateer et al., 1999). Previous field studies of the BioSand Filter have reported removal efficiencies of *E. coli* between 1 and 2 log reduction (94%: Stauber et al., 2006; 98.5%: Duke et al., 2006) and that the rate of sustained use can be as high as 70% five years after installation (Earwaker, 2006). Furthermore, there is health-based evidence that the filters can reduce diarrheal disease by an estimated 30 percent to 40 percent, in particular amongst highly vulnerable children less than 5 years old (Sobsey, 2007).
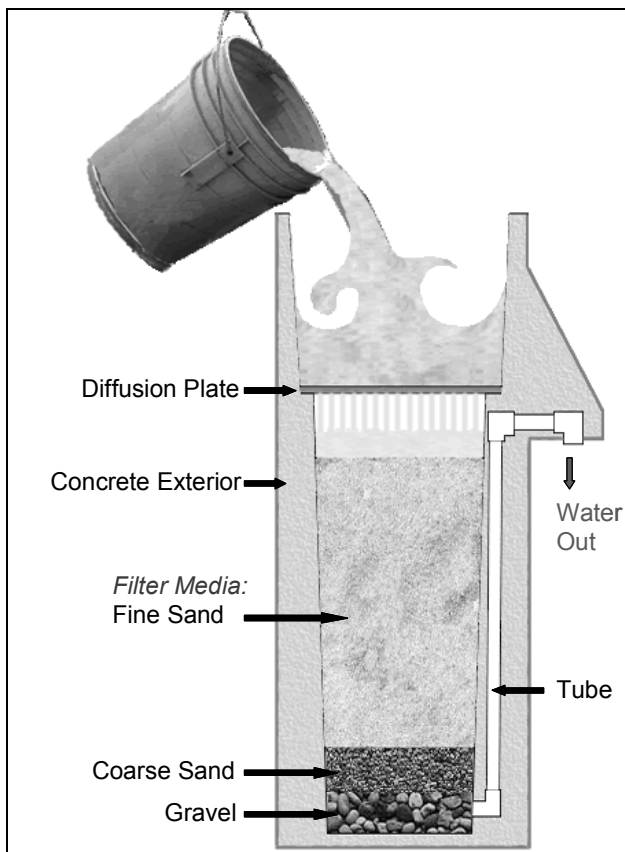
Figure 4.2 Schematic of BioSand Filter. Source: Clean Water for Haiti (2003).

The filter is operated by pouring approximately 20 L of source water into the top of the filter, displacing an equal volume of filtered water through the outlet, which is then stored for subsequent consumption. The Center for Affordable Water and Sanitation Technology (CAWST) recommends following filtration with some form of disinfection and that the post-filtered water be safely stored in a container with a lid and out of reach of animals and young children (CAWST, 2006). Maintenance of the BioSand Filter is important because over time the pores in the filtration media become plugged which significantly reduces the flow. This is corrected by *harrowing*: manually stirring the standing depth of water to suspend the sediment in the top layers of sand, and scooping out the dirty water. There are currently no specific guidelines regarding maintenance frequency, but CAWST recommends harrowing only when the flow is reduced such that the filter no longer provides sufficient water for the household;

washing too frequently prevents the biological layer from fully developing which can reduce filtration efficiency (CAWST, 2006).

The capability of the filter to significantly reduce microbial contamination, and the relative ease to operate and maintain, made the BioSand Filter an appropriate candidate HWT technology to be implemented in the rural communities of Posoltega.

4.1.1.3   Field Evaluation of BioSand Filters in Posoltega

A field study of the BioSand Filters in Posoltega was conducted from January to April 2007 by researchers from the University of British Columbia (UBC) in collaboration with CAWST and CIRA, with assistance from the "Alma Nubia López" Health Center of Posoltega. The objectives of the study were as follows:

- Characterization of the physical condition and operation of the BioSand Filters 8 years and 3 years after installation (i.e. post-1999 and 2004 respectively);
- Determination of the microbial and turbidity removal efficiency of those BioSand Filters still in operation;
- Evaluation of the BioSand Filter as an intervention for the protection of human health within the rural communities of Posoltega, Nicaragua.

Presented in this Chapter are the socioeconomic profile of the study population and the issues that point to the failed BioSand Filter implementation project in Posoltega, and how these issues could have been identified and mitigated through the application of a more holistic approach to the delivery of safe water, such as the World Health Organization Water Safety Plan. Chapter 2 presents a discussion of the efficacy of the BioSand Filter, and Chapter 3 presents an evaluation of the field water quality testing methodology.

4.1.2   Socioeconomic Profile

A total of 134 people were accounted for directly in the survey of the 24 households where the BioSand Filter was found to be in use, plus an additional 16 people from three families who used a shared filter, for a total study population of 150 (27 households). The socioeconomic

profile of the study population is a good representation of the population of the rural communities in Posoltega.

4.1.2.1   Demographics

The age and gender distributions of the study population are presented in Figure 4.3. Family sizes ranged from 2 to 10 people, with an average family size of 5.5 people. Family composition often consisted of extended family members, including multiple generations and offspring from previous relationships. Young people tended not to establish new homes on their own, as indicated both by the family size, and the median age of the head of household being 52.
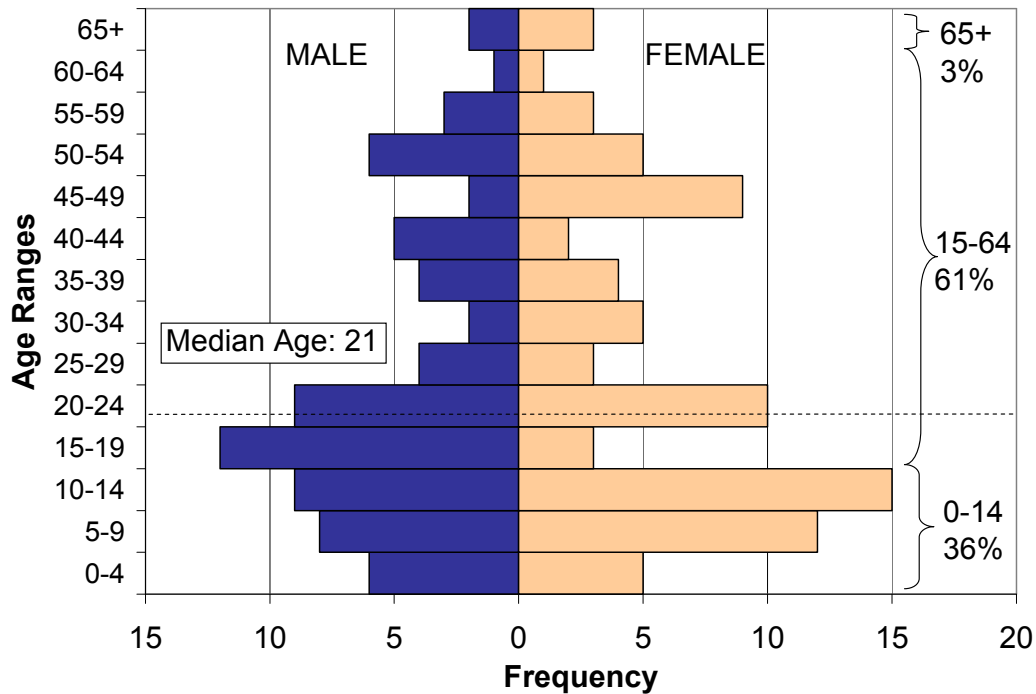
Figure 4.3   Age and Gender Distribution of Study Population

4.1.2.2   Employment and Education

The primary economic activities of the age group 15 to 64 are presented in Figure 4.4. Approximately 44% of the families owned small parcels of land for agricultural production, and working this land was the primary activity for the male heads of these households; male family members typically worked as *obreros* (farmhands or labourers) on these same lands. Roles in

which females participated in economic activity included working as school teachers, shopkeepers or domestic servants.
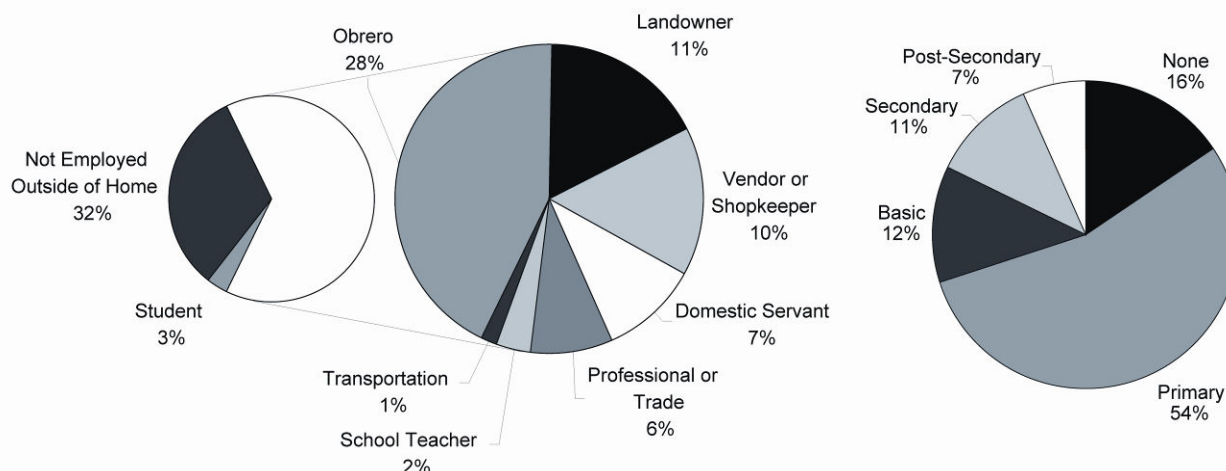
Figure 4.4   Primary Economic Activities and Highest Level of Education Achieved for Age Group 15-64.

The total number of students aged 5 through 14 in the study population was 40 and the enrolment rate was 91%. The highest level of education achieved amongst the adult population is shown in Figure 4.4. The adult literacy rate was 85%.

4.1.2.3   Community Infrastructure

The majority of families had built their own homes which were typically composed of concrete block walls, earth floors and sheet metal roofs. Other common construction materials included wooden boards and sticks, plastic sheets, sheet metal and brick for walls, and ceramic tiles for the roof. Seven houses had floors that were finished with either concrete or ceramic. Twenty one of the 27 households had access to electrical power, although it was indicated by one community leader that every connection was an illegal connection and no utilities were paid. Nearly every household with electricity also had a television, and six households had either a refrigerator or freezer. Only one family had a motorized vehicle: a broken-down farm tractor.

Twenty five families had their own shallow well. Seventeen of these wells had mechanical pumps for water extraction, while the rest relied on a bucket and rope. Fourteen of the wells had

some form of semi-permanent cap to protect the well water from environmental contaminants. The majority of families let animals such as chickens and pigs run freely in the yard, with little or no control to keep them away from the well area. Twenty of the houses had a double-vaulted ventilated latrine constructed by World Vision in the years following Hurricane Mitch. The others had pit latrines with a makeshift enclosure. Fifteen latrines were found to be in a reasonably clean and hygienic condition.

Another post-Hurricane Mitch intervention introduced into the community of El Trianón was a Bio-Gas generator, which used the anaerobic decomposition of animal waste to produce methane gas that was piped directly to a stove in the kitchen. Nearly every household in El Trianón received a Bio-Gas generator from a non-governmental organization from Managua called Ciprés. At the time of the evaluation only six were found to be in working order; the others had ruptured rubber membranes which had not been repaired. Burning biomass for cooking was nearly ubiquitous, even for those families that had functional Bio-Gas generators. Only one family had a propane stove which they used exclusively for cooking.

The organizations mentioned above were not involved in the installation of the BioSand Filters in Posoltega.

4.1.2.4 Community Health Services

The Nicaraguan *Ministerio de Salud* (Ministry of Health, MINSA) provides health services to the people of Posoltega through the newly constructed "Alma Nubia López" Health Center, located approximately 1 km north of the urban town center. The facility provides general medicine, obstetrics, prenatal and pediatric care, dentistry, immunizations, a laboratory and 24-hour emergency services. The rural and remote communities are serviced periodically by outreach programs, clinics and medical staff from the health center on rural rotations.

The health center has limited resources to undertake microbial water quality testing. The water quality in the urban town center is monitored by testing for chlorine residual, which is performed by the local hygienist.

4.1.3 Filtration Efficiency of the BioSand Filter

The outcome of the water quality testing at the 24 households that still had an operating BioSand Filter is presented in Figure 4.5. The average removal efficiency for *E. coli* and total coliforms was found to be 96% and 98% respectively. These removal efficiencies are consistent with other field evaluations of the BioSand Filter which have reported removal efficiencies of *E. coli* between 94% (Stauber et al., 2006) and 98.5% (Duke et al., 2006). There was no statistically significant difference detected between the removal efficiencies of the filters from 1999 and 2004, suggesting that there is no long-term decrease in filter performance provided that the filter is operated properly. A further discussion of the filtration efficiency is presented in Chapter 2.
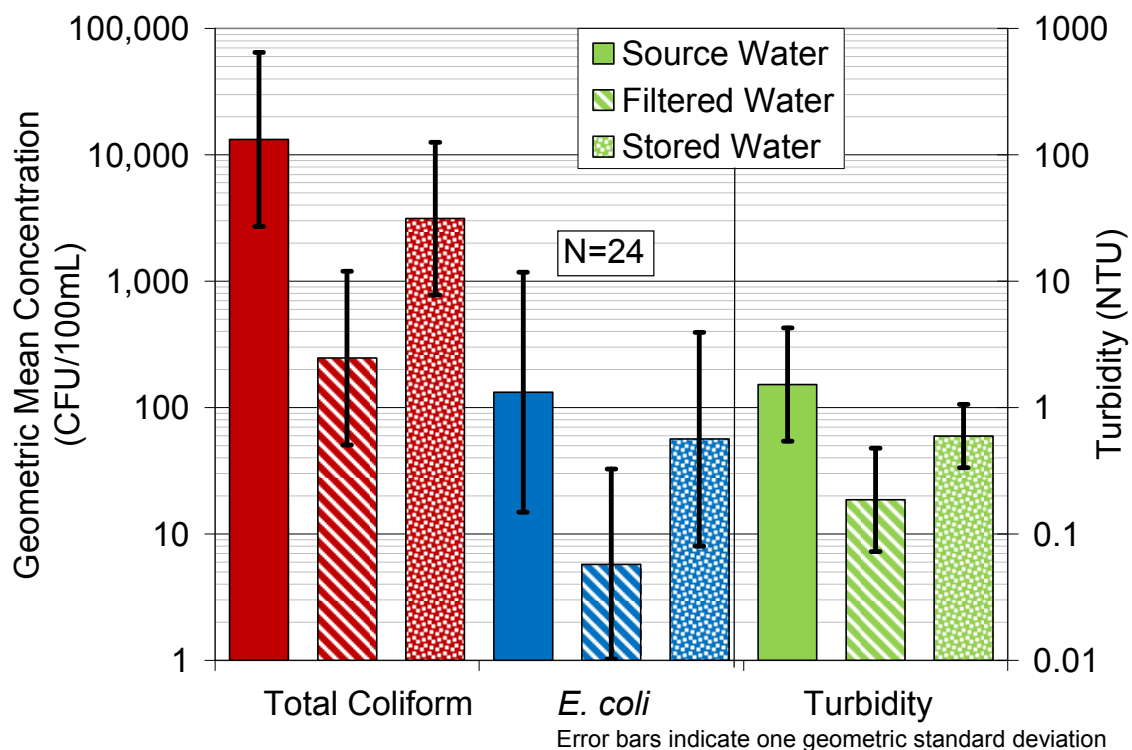
Figure 4.5   Water Quality Results of Source, Filtered and Stored Water

The WHO Guidelines for Drinking Water Quality that were in place at the time of the initial installation state that "*E. coli* and thermotolerant coliform bacteria must not be detectable in a 100 mL sample" of water intended for drinking (WHO, 1993). Thus, while the BioSand Filter does provide progressive improvement over the raw source water, the filtered water does not meet the standard on account of *E. coli* contamination. Furthermore, the stored post-filtered water exhibits approximately one order of magnitude higher contamination than the filtered water as a result of regrowth and recontamination.

Turbidity removal was 88%, although the source water was generally quite clear with 48% reporting below 1.0 NTU and 67% reporting below 3.0 NTU. The current WHO Guidelines for Drinking Water Quality suggest that a turbidity of less than 5 NTU is aesthetically acceptable to consumers (WHO, 2006), and this was achieved in the filtered and stored water.

4.1.4   Sustained Use of the BioSand Filter

Of the 234 BioSand Filters installed in Posoltega between 1999 and 2004, only 24 were still found to be in operation, representing a rate of sustained use of only 10%. However, amongst the users of those 24 filters, there was a very high level of acceptance of the technology. During the interviews with the filter users, every respondent said that they liked the filter and that they would recommend its use to others. The vast majority of the respondents indicated that they felt that the filter improved various aspects of the quality of the drinking water, in taste (88%) odour (80%) and appearance (72%). The cooling effect of the concrete filter was another benefit that was commonly cited. In addition, 88% of the respondents felt that the health of their family had improved since they had started to use the BioSand Filter to treat their drinking water.

The separate rates of sustained use for the 1999 filters and 2004 filters are 30% and 7% respectively. The remaining filters were found to be in various states of disuse and disrepair: cracked, leaking, broken, dismantled, emptied or otherwise abandoned and unused. The principal

cause for disuse was structural failure in the concrete filter walls, particularly for the 2004 filters. A further discussion of the failure mechanisms can be found in Chapter 2.

4.1.4.1   Failure Mechanisms of 1999 Filters

Of the 34 filters installed in El Trianón in 1999, only 10 were found to still be in operation; the rest were broken or abandoned. When the filters were being implemented, the community was in the process of relocating approximately 500 m to the north to avert future flooding (Baughen et al., 1999). While the relocation was still underway, some families received filters at their homes in the original community location, and many of the filters were damaged during the transition. Other filters were abandoned altogether at the old homes when the family moved to their new homes or away from El Trianón completely.

The implementation of the 2004 filters and their subsequent failure was another indirect cause for failure of some the 1999 filters. In some cases the families in El Trianón that received a second filter in 2004 disassembled their otherwise operational 1999 filter; when the 2004 filter failed the family was left without any operational filter to use.

4.1.4.2   Failure mechanisms of 2004 filters

Of the 200 filters installed in 2004, only 14 were found to be in operation. By far the most common reason identified for the disuse of the other filters was significant cracking associated with structural failure of the concrete walls, causing the water and sand to leak from the filter. These filters were built by community members under the direction of the NGO technicians at the local health center. Anecdotal evidence suggests that the concrete was not given sufficient curing time to achieve any significant strength and durability before they were loaded onto carts to be transported across rural dirt roads to the communities.

4.1.5   Operation and Maintenance of the BioSand Filters

The users of the 24 BioSand Filters found to be in operation were interviewed regarding the operation and maintenance of the filter. When questioned about what prompted them to clean the

top layer of sand in the filter, eight users responded correctly "when the flow was slow". The other responses were split between "when the top of the filter looked dirty" and "on a regular schedule". The reported cleaning frequencies ranged from "every two days" to "once in the last year", with an average of approximately once per month.

Not one of the filter users used any form of post-filtration disinfection on the stored water. Five users did not have a lid for their water storage containers and the vast majority left the storage container on the ground beside the filter even when there was no flow, where it was accessible to children and animals. For extracting stored water, ten families used a dedicated cup or ladle, or used a storage container with a spout; the other families dipped any cup and were sometimes observed dipping their hands when extracting water from the storage container. The impact of the unsafe storage of water can be seen in Figure 4.5, where the stored water exhibited approximately a full order of magnitude greater concentration of *E. coli* and total coliforms than the filtered water, and does not meet the WHO guidelines for drinking water quality.

When users were asked about the training they had received, the majority reported that they had participated in a one-day training seminar given to the community as a group by the NGO at the time of the installation, and had received a single page of printed instructions. About half of the users recalled receiving a follow-up visit from a representative from the NGO anytime after the initial installation.

4.2   Issues

At the end of the study, the only conclusion was one of complete program failure. The modes of failure were insufficient technology for the field conditions, structural failure of filter units at the implementation stage, insufficient user training, and failure to develop community resources.

4.2.1   Insufficient Technology

The BioSand Filter is an appropriate technology for rural and remote locations without access to a centralized treatment system. When properly used and maintained, it can be relied

upon to provide between 1 and 2 log reduction (90 to 99%) of microbial contamination across the filter. However, the filters will not deliver clean water in isolation of consideration of source water quality and/or additional treatment including disinfection.

The shallow wells in the rural communities of Posoltega were found to exhibit high levels of microbial contamination (Figure 4.5). The BioSand Filters were found to provide average reductions of 96% and 98% respectively for *E. coli* and total coliforms, and as such this is a progressive improvement over the raw source water. However, the filtered and post-filtered water did meet the criteria for safe water, on account of the presence of *E. coli*. When the BioSand Filters were implemented, there was a failure to adequately address the source water quality, and undertake the appropriate works to protect the wells. There was also a failure to stress the importance of post-filtration disinfection to the filter users.

4.2.2 Structural Failure

Only 10% of the BioSand Filters installed in Posoltega in 1999 and 2004 were still found to be in use. The primary cause for disuse of the other 90% was structural failure in the concrete walls of the filter, causing water to leak onto the floor or onto the ground. Anecdotal evidence suggests an overall lack of quality control during construction and implementation, particularly of the 200 filters from 2004. Insufficient curing time was given to the concrete structure after being removed from the molds during construction, and there was a general lack of care during the transport and delivery of the filters to the recipient households.

That so many of the 2004 filters failed as a result of improper construction indicates a failure in technology transfer, either as a result of a lack of communication or a lack of understanding of the physical characteristics of the materials being used. The latter indicates gross incompetence and is not excusable.

4.2.3 Insufficient Training

The user responses regarding the operation and maintenance of the filters and the safe storage of post-filtered water indicate that there was insufficient training to the filter users as well as insufficient follow-up. The lack of post-filtration disinfection and the unsafe storage of post-filtered water are confirmed by the microbial water quality of the stored water (Figure 4.5) which indicates regrowth and recontamination.

4.2.4 Failure to Develop Community Resources

In Posoltega, there were no community resources available for the BioSand Filter; there were no trained individuals in either the rural communities or the urban town center to provide expertise in operation, maintenance or reparation of the filter. Replacement parts such as the lid, diffuser plate and outlet pipe were not readily available; they could be constructed or make-shifted from available materials, but the expertise did not exist locally. The existing local health networks, including the health center and municipality were only vaguely familiar with the technology and therefore could not provide the required support. There was expertise based in Managua but this was essentially unreachable by the local community. The absence of local expertise became the critical HWT system failure when the structural integrity of the BioSand Filters failed, as there were no community resources available for users to get assistance for repairs or replacements.

4.2.5 Outcome of Failure

In the developed world, the application of a technology for the delivery of safe water without sufficient training of the operators and access to the resources required for operation and maintenance would be considered unacceptable. Worse yet is the scenario where 90% of the technology units structurally failed essentially upon delivery. Yet, this is exactly the case of the BioSand Filter implementation program in Posoltega, so the outcome of failure should not be a surprise.

The outcome of the failure of the BioSand Filter implementation program in Posoltega was detected in the negative perspective toward the collaborative process for water and health issues. Many people understood that their well water was contaminated, but seemed resigned to the idea that there was nothing they could do about it. For the communities that received 2004 filters, the community members themselves provided labour for the construction of the concrete filters, only to experience the structural failure of these units in more than 90% of the cases. In the community of San Agustín, where not a single filter in working condition was found during the evaluation, individuals expressed their anger and disappointment when questioned about the BioSand Filter with responses of "*no sirve*", which translates to "it's useless" in the most pejorative sense, and rightfully so given the circumstances. This perspective will make it more difficult for future aid organizations attempting to implement alternative forms of HWT, or even to repair the existing BioSand Filters as they will face strong resistance. Getting community support for such a project will be more difficult than had the failed BioSand Filters not been introduced in the first place. In this regard, the failed HWT implementation program in Posoltega caused more harm than good.

4.3   Lessons Learned

The majority of the failures of the HWT implementation in Posoltega could have been identified and mitigated through the application of a system approach to the delivery of clean water, such as the WHO Water Safety Plan (WSP). The components of a WSP, the system assessment, the operational monitoring and management, are presented below, and how they could have been used to mitigate the failures of the HWT implementation in Posoltega.

4.3.1   System Assessment and Design

The system assessment component of a WSP is intended to determine whether a particular system is appropriate for delivering water that meets specific health-based criteria. In the case of HWT, this includes a verification of whether a particular household scale technology is capable

of meeting water quality guidelines given the existing source water quality, and is appropriate for the particular socioeconomic conditions in the community. If a particular technology is insufficient, additional measures should be implemented, including the identification of alternative water sources, or providing better protection for existing sources, and applying additional treatment including disinfection.

It has been demonstrated that the BioSand Filter is capable of providing between 1 and 2 log reduction (90 to 99%) of microbial contamination. However, the BioSand Filter alone is not capable of providing safe water that meets the WHO guidelines in the absence of consideration of source water and additional treatment including disinfection.

Studies into the groundwater in the Posoltega region have indicated that there are essentially two aquifers: a shallow aquifer which exhibits persistent pesticide contamination from widespread use during the 1950s through to the 1970s, and a deeper aquifer that is recharged from the nearby volcano range and is relatively pristine (Moncrieff, 2006; Calderón and Bentley, 2007). The urban town center of Posoltega extracts water from the deeper aquifer, as do a small number of the rural communities including La Virgin.

Having to relocate the entire community following Hurricane Mitch, La Virgin received substantial aid from the Spanish International Cooperation Agency (AECI) for community infrastructure. This included the construction of a home for each of the 85 families, a water system incorporating a deep perforated well, a water tower and distribution system, and a sanitary collection system with a communal septic tank. AECI helped La Virgin develop a water committee which charges families 100 Córdobas (approximately $5 US) per month to operate and maintain the system. Water quality testing found that the drinking water was significantly better than the filtered water in the communities that relied on the BioSand Filter.

When alternative source water is not feasible due to financial or physical constraints, there are cost-effective means of providing protection for shallow wells against environmental

contaminants. These include the installation of a mechanical pump, concrete collar and semi-permanent cap on all of the remaining open wells, raising the ground at the well location to promote runoff away, and enclosing with a fence to prevent animals from accessing the well.

Chlorination of the post-filtered water is a simple, cost-effective method of disinfecting pathogens that may have passed through the filter, while the chlorine residual will inhibit regrowth and recontamination of the stored water. The US Environmental Protection Agency (USEPA) recommends using 1/8 teaspoon of household bleach (5.25% sodium hypochlorite) per gallon of water (USEPA, 2007), which is equivalent to 3 mL of bleach per 20 L bucket for a dose of 8 mg/L of chlorine. The solution is to be mixed well and allowed to sit for 30 minutes. A simple and cost-effective method that could be used to administer the approximate required dose of bleach to a 20 L bucket of filtered water is a single pump from an ordinary liquid hand soap dispenser. This could be administered to the bucket used to collect filtered water near the beginning of the filtration period to achieve both the mixing and the pause period. As both the household bleach and the hand soap dispenser are readily available in the urban town center of Posoltega, this method of chlorination can be promoted as an effective means of disinfection.

With a WSP in place, the system assessment would have identified the limitations of the BioSand Filters alone to meet the water quality guidelines and stressed the need for additional steps such as the identification of alternative water sources or better protecting existing sources, and the need for additional water treatment including disinfection. The capacity and resources exist within the communities to undertake the works described above for source protection and disinfection.

4.3.2 Effective Operational Monitoring

The operational monitoring component of a WSP is to ensure that the control measures are being properly implemented to ensure the safe delivery of water. In the context of HWT this

includes all of the steps from the technology construction and delivery, user training, monitoring of control measures and evaluation.

The most visible failure of the BioSand Filter program in Posoltega was the structural failure of more than 90% of the filters from 2004. At minimum, some quality control during the construction of the filters would have identified the significant rate of structural failure, and steps could have been taken to mitigate the problem. The robustness of the BioSand Filters is demonstrated in those filters that are still in operation 8 years after installation. This suggests that in the absence of structural failure, the rate of sustained use could have been on the order of 70%, as suggested in other long-term field studies (Earwaker, 2006).

Follow-up with the filter users would have identified the improper filter maintenance practices and unsafe storage of the post-filtered water, highlighting the need for additional operator training. Ideally, the training program should entail several follow-up consultations with the filter users, reinforcing key concepts. The training should also stress the importance of a post-filtration disinfection method such as the chlorination dosing described above. The one-day training seminar and the single page of printed instructions provided by the NGO did not appear to be sufficient.

The socioeconomic data collected during the 2007 evaluation indicates that the vast majority of the population is literate and has at least a primary level of education, and that people are involved in a variety of different economic activities. Most of the families have built their own house and utilize a variety of community infrastructure of different complexity. All of this indicates that the population is generally receptive to new information and able to be taught, and have a breadth of different skill sets. However, the skills required to properly use and maintain the BioSand Filter are not necessarily intuitive (e.g. maintenance frequency should be minimized for optimal results) and concepts such as microbial contamination can be difficult for lay persons

to grasp. Therefore, the training methods need to address the socioeconomic reality existing in the population in order to be effective.

The operational monitoring should include water quality testing to ensure that the health based targets for water quality are being met. If the population can be persuaded to use chlorine for post-filtration disinfection, then testing for chlorine residual can be used as a proxy test for confirming the absence of microbial contamination. Testing for chlorine residual is a simple and inexpensive test, without the need for sterilization, concentration and incubation associated with microbial testing methods. A chlorine testing program of stored water can be used to evaluate this control measure, while simultaneously reinforcing the use of chlorine by the filter users. In Posoltega, the capacity and resources for testing chlorine residual exist at the local health center.

With a WSP in place, operational monitoring of the BioSand Filter implementation program would have readily identified the problems of the faulty filter construction, improper maintenance practices and unsafe water storage, and steps could have been taken to rectify these problems.

4.3.3 Management

Effective management as part of a WSP includes normal system operation, as well as the actions taken and resources available in the event of incident situations or system failure. In the context of a piped community system, this includes the supply chain of consumable resources used on a daily basis as well as the availability of replacement parts for maintenance and when faced with incident situations. In the context of HWT, effective management requires resources to be available where users can get additional training or troubleshooting advice, and replacement parts or repair materials in the event of component failures.

International development literature stresses the importance of incorporating capacity building of community resources as part of any development project. The Central American Water Resources Management Network (CARA) *Trabajando Juntos* ("Working Together")

handbook (2004) provides detailed guidelines on strengthening local health networks when implementing any water and sanitation project through collaboration and communication. Such a process ensures that when a water system is implemented, either a community system or HWT, it meets the needs of the community, and that there exists sufficient capacity and resources to operate and maintain the system.

With a WSP in place, local community resources could have facilitated the BioSand Filter implementation in Posoltega, and possibly prevented the failure of the project. It is for this reason capacity development and strengthening of existing health networks needs to take priority over the implementation of any particular HWT technology. With the right training, individuals and networks not only become community resources for the management of the HWT implementation program, but also increase the capacity of the community to address water, health and sanitation issues.

4.3.4 Conclusions

The case study of BioSand Filters in Posoltega demonstrates how a household water treatment program can fail when implemented in the absence of a system approach framework. The failures encountered in Posoltega were not specifically related to the BioSand Filter technology; water quality testing demonstrated that the filters were operating as expected, providing an average of 96% reduction in *E. coli* when evaluated three and eight years after installation. Rather, the failures relate to not addressing the limitations of the technology, structural failure of the technology units at the implementation stage, insufficient training for the users, and a failure to develop community resources.

A system approach such as the WHO water safety plan could have identified and mitigated the majority of the failures encountered in Posoltega. The system assessment would have considered the limitations of the BioSand Filter given the high level of contamination of source water, indicating the need for alternative sources or source protection, coupled with additional

treatment including disinfection. The operational monitoring would have identified the structural failures of the filters, as well as the need for further user training regarding maintenance and safe water storage. The effective management of the WSP would have prioritized the capacity building and development of community resources required for the successful execution of a HWT implementation program.

In general, the resources required to develop a system approach for a HWT implementation program are not significantly greater than the HWT implementation program itself, and the capacity to develop and apply the system approach often already exists within the community. This begs the question: is the implementation of HWT technology in the absence of a system approach ever appropriate, or is it sufficient to implement a HWT technology in the absence of a complete system and thereby provide some minimal benefit?

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5   CONCLUSIONS AND RECOMMENDATIONS

5.1   Conclusions

This research project was an evaluation of the use and performance of the BioSand Filters in Posoltega, Nicaragua. In addition, a follow-up QA/QC program was undertaken to evaluate the field water quality testing methods used. The conclusions that can be drawn from the study are summarized below:

5.1.1   Efficacy of the BioSand Filters

Of the 234 BioSand Filters installed in Posoltega, Nicaragua during the 1999 and 2004 implementation programs, only 24 filters were found to still be in operation. This is a rate of sustained use of only 10%. The most significant cause of failure in the filters was cracking in the concrete structure.

Water quality testing of the 24 BioSand Filters found to be in operation indicated that they were providing average filtration efficiencies of 98% for total coliforms, 96% for *E. coli* and 88% for turbidity. There was no statistically significant difference between filters from 1999 and 2004, suggesting that there is no long-term decrease in filter performance provided that the filter is maintained in operation. These values are also consistent with other field evaluations of the BioSand Filter, indicating that the filters that were in operation were operating as expected. However, the filtered water and post-filtered water did not meet the World Health Organization (WHO) guidelines for drinking water quality because of the presence of *E. coli* (WHO, 2006). When used to treat highly contaminated source water, the filters can not deliver clean water in isolation. Additional treatment involving disinfection will always be required.

The log removal of the filter was found to have a statistically significant correlation with the logarithm of the source water contamination. This relationship can be used to develop predictive models that health and policy decision makers can use to predict health outcomes under different environmental scenarios that may impact source water quality.

The log removal was found to have a statistically significant negative correlation to the flow rate through the filter, an expected outcome. The data from this research supports the new policy from CAWST on reducing the maximum recommended flow rate through the filter to 0.6 L/min (CAWST 2007).

The log removal was found to have a statistically significant correlation to the standing depth of water above the sand during the pause period. This is contrary to the recommendations of Buzunis (1995) who recommended minimizing the standing water depth based on a model of oxygen transfer. This suggests that preventing disruption to the biological layer may be more important for filtration efficiency. Further investigation is recommended in determining the statistical significance of this relationship with a larger sample size drawn from available data from other field studies. If this hypothesis is true, then one possible alteration to the design of the BioSand Filter is to submerge the diffuser plate, and thereby further reduce the disturbance to the biological layer when pouring water into the top of the filter. Such a design change would however have to consider the transfer of oxygen to the biological layer during the pause period to prevent the development of anaerobic conditions.

No statistically significant correlation was identified between filter efficiency and the total daily loading of the filter. This suggests that there are no negative impacts of multiple families sharing a single BioSand Filter for their drinking water, and that this can be promoted as a standard practice when one family's filter is broken or simply down for maintenance.

5.1.2 Microbial Water Quality Testing Methods

The QA/QC work demonstrated that the membrane filtration (MF) technique with m-coliBlue24 growth media was able to produce useful reproducible results, and is an appropriate method for conducting field water quality testing. When compared to the spiked organism concentration, the MF technique tends to underestimate. This may be due to a variety of factors, including organisms that are strained or even killed on the membrane during the

membrane filtration, or organisms clinging to the interior equipment walls in spite of the rinsing techniques. Nonetheless, the MF technique appeared to be accurate to an order-of-magnitude level of precision which was sufficient for the purposes of this study.

The average coefficient of variation associated with averaging across different sample volumes was found to be 44% in the laboratory and 51% in the field; no statistically significant difference was detected between the laboratory and field data set, suggesting that the study results would not have had any less random error had the water samples been collected and transported to a controlled laboratory facility for testing. In order to minimize the error associated with the techniques, the filtered volume should be selected such that the number of organisms is between approximately 15 and 150 colonies. This is consistent with recommendations from Standard Methods (APHA 1998).

Colonies formed from a random sample of duck pond water were identified using the independent methods of the API 20E test strips. Five of six blue colonies tested were identified as *E. coli* and all five of the red colonies tested were identified as species belonging to the coliform group. Coupled with the successful suppression of *E. faecalis* as a background organism during the QA/QC analysis, the m-coliBlue24 appears to provide a high level of confidence in organism identification.

The SolarCult Dipslides may be an appropriate tool for performing preliminary microbial testing in situations where other resources are not available. The number of colonies on the MacConkey side of the dipslide can be used to provide an initial estimate as to the severity of microbial contamination of a raw water source, and provide an indication as to the appropriateness of any health intervention. As the limit of detection is approximately 1000 CFU/100 mL, and the BioSand Filter can reasonably provide a log-reduction of 2, any growth on the MacConkey side of the dipslide would provide an indication that the BioSand Filter should

not be used in isolation to provide clean drinking water, and additional treatment requiring disinfection would be required.

The dipslides can also be used as a tool for local health representatives to promote safe water practices in the community, as they provide a means of visually demonstrating the concept of microbial contamination in a way that is clearly understood.

It is not recommended that the dipslides be used as a presence / absence test for the detection of *E. coli*; the high limit of detection of approximately 1000 CFU/100 mL leaves open the possibility for false negatives within the range of concentrations that can be hazardous to human health.

5.1.3   System Approach to Household Water Treatment

The BioSand Filter implementation program in Posoltega, Nicaragua exhibited failure at many levels. These failures included the failure to address the limitations of the technology to adequately provide safe drinking water given the source water contamination, the structural failure in up to 90% of the BioSand Filters installed which resulted in a rate of sustained use of only 10%, the failure to provide adequate training and education to the filter users on the proper filter operation and maintenance, on the need for post-filtration disinfection and on the safe storage of water within the home, and the failure to develop community resources to provide local expertise with regard to the BioSand Filter.

Many of these problems could have been mitigated through the implementation of a holistic system approach to the implementation of HWT, such as the World Health Organization Water Safety Plan (WSP), which consists of a system assessment, operational monitoring and management (WHO 2006).

The system assessment would have identified the limitations of the BioSand Filters alone to meet the WHO guidelines for drinking water quality and stressed the need for additional steps such as the identification of alternative water sources or better protecting existing sources, and

the need for additional water treatment including disinfection. The capacity and resources exist within the communities to perform the recommended tasks, such as providing better well protection and disinfecting filtered water and stored post-filtered water with chlorine bleach.

Operational monitoring of the BioSand Filter implementation program would have identified the problems of the faulty filter construction, improper filter maintenance practices and unsafe water storage within the home. These problems could then have been mitigated through better quality control during filter construction, in particular allowing the concrete filters to cure for five to seven days before being transported to the rural communities. Educational programs could have been developed that were more socially appropriate for the people in the communities.

The development of community resources could have facilitated the management of the BioSand Filter implementation in Posoltega, Nicaragua and possibly prevented the failure of the project. It is for this reason that capacity development and strengthening of existing health networks needs to take priority over the delivery of the treatment units when implementing any particular HWT project.

The case study of BioSand Filters in Posoltega demonstrates how a household water treatment program can fail when implemented in the absence of a system approach framework. The 10% of the BioSand Filters that were still in use were operating as expected, providing 98% reduction in total coliforms and 96% reduction in *E. coli*, three and eight years after installation. However, the failure to provide a holistic system approach to the delivery of safe water left the majority of these communities exposed to significant health risks. In general, the resources required to develop a system approach for a HWT implementation program are not significantly greater than the HWT implementation program itself, and the capacity to develop and apply the system approach often already exists within the community. This begs the question: is the implementation of HWT technology in the absence of a system approach ever appropriate, or is

it sufficient to implement a HWT technology in the absence of a complete system and thereby provide some minimal benefit?

5.2 Strengths and Limitations

One strength of this research project is the demonstration that a rigorous water quality testing protocol can be followed in the field by a small research team with limited budget and resources, and achieve meaningful and reproducible results. Thus, future evaluations of the BioSand Filter and other forms of Household Water Treatment can be conducted by researchers under similar circumstances. With only a small amount of training and access to the right resources, such evaluations could be conducted by representatives from the corresponding health centers, or even individuals from the impacted communities themselves.

Another strength of this type of research is the opportunity to work in the community and interact with the people who are directly impacted by the technology. By working with the community members, the research team gained intimate knowledge about the role that the BioSand Filters played in bringing the communities together to address their health issues. Furthermore, the community benefits from the knowledge transfer through interaction with the researchers, receiving feedback regarding the filter use, and the reassurance that there are individuals who have concern for the health of the community.

A limitation of the research project was the outcome of finding only 24 operational BioSand Filters. This small population limited the statistical power of the correlations drawn from the study, thus leading to a higher possibility of rejecting a true null hypothesis (Type I error). Nonetheless, the evaluation of a failed implementation project allowed for the exploration of the underlying causes of failure, as discussed in Chapter 4.

Another limitation of the research was the difficulty frequently encountered when enumerating the colonies that formed on the membrane using the m-coliBlue24 growth media. Numbers for total coliforms were frequently upwards of 1000 CFU. While this was beyond the

maximum as recommended by Standard Methods (APHA, 1998), enumerating the colonies for this sample permitted at least an order-of-magnitude approximation to the concentration, which was then sufficient for computing the filtration efficiency as a log-reduction. Above approximately 1000 colonies, the concentration was estimated by averaging the count from five randomly-selected squares printed on the membrane, and factoring up by 100, which is the ratio of the area of one square to the exposed area of the membrane when locked below the reservoir tube of the membrane filtration apparatus. Other problems with the membrane filtration using m-coliBlue24 included the incidences of smudging or growth on the unexposed outer ring, the growth of black colonies instead of blue, and colourless confluent growth resulting from very high organism concentrations. It is unclear how many of the colour or growth problems relate to temperature sensitivity of the m-coliBlue24. Further research is needed to determine what impacts insufficient refrigeration during the transportation or storage of the m-coliBlue24 will have on the microbial results, particularly in tropical locations where ambient temperatures are high and access to refrigeration may be limited.

5.3   Recommendations

This research project into BioSand Filters in Posoltega, Nicaragua provided insight into an example of a HWT project that was improperly implemented. The failures of this project represent a lost opportunity to provide clean drinking water to the families of the communities of El Trianón, San Gilberto, Posolteguilla, Buenos Aires, El Mojón and San Agustín. In addition to the fact that these families continue to be exposed to significant health risks from drinking untreated contaminated drinking water, they have also experienced a betrayal of trust by the implementing NGO. This betrayal will make it more difficult for future aid organizations to bring water, health and sanitation projects to these communities. It is hoped that the amelioration of the failed BioSand Filter implementation project be prioritized by the appropriate organizations to correct this betrayal.

As with any work in rural and remote communities in the developing world, the most important element for the successful completion of this research project was the development of a respectful and trustful relationship with community members. This included networking with the appropriate individuals to be introduced to the community leader, and communicating with everyone openly, honestly and as a privileged guest. It is recommended that future researchers in similar settings build in sufficient time in their project schedules for the development of these relationships.

The evaluation of Household Water Treatment (HWT) falls into three distinct categories: laboratory evaluation, field evaluation, and health impact evaluation. The outcome of this field evaluation clearly demonstrates why it is critically important that a field evaluation be conducted in advance of a health impact evaluation; it would be inappropriate to attribute any health improvement detected amongst the study population to the BioSand Filters, when only 10% of the population have filters that are still in operation. It is therefore not recommended that a health impact evaluation of BioSand Filters be conducted in Posoltega, Nicaragua at the present time.

Using membrane filtration with m-coliBlue24 growth media is a recommended approach for microbial water quality testing for future field evaluations of the BioSand Filter. Filtering different volumes (1 mL and 10 mL for source water, 10 mL and 100 mL for filtered and stored water) was found to be very effective for the levels of contamination encountered in the study. Depending upon the severity of source contamination, the ability to measure a 0.1 mL sample in the field without contaminating the sample may also be of benefit.

Using questionnaires and inspection forms can be an effective method of collecting household demographic and community infrastructure data to develop socioeconomic profiles. It is recommended that the assistance of a local expert be sought to ensure that all of the necessary questions are framed in a culturally appropriate manner. For example, the original questionnaire

used the same employment categories as the national census, but this had to be refined to better

capture the diversity of economic activities that took place within the communities.

5.4   References

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APPENDICES

Appendix A: Raw Data

Table A.1   BioSand Filter Data

ID#	Community	GPS Coordinates		Filter Year	Filter Material	Flow Time (s)	Standing Depth (cm)	Filter Location	Filter is Level	Filter is Clean	Filter has a lid	Filter has a Diffusor	Filter has a Spout Cover	Filter Food Storage	Filter Leaks
		Latitude	Longitude												
A1	El Trianón	12-31-36.5	86-59-32.4	1999	Plastic	45.8	8.5	Inside	Y	N	Y	Y	N	N	N
A2	El Trianón	12-31-38.0	86-59-30.1	1999	Plastic	44.0	20	Inside	Y	Y	Y	Y	N	N	N
A3	El Trianón	12-31-37.1	86-59-33.4	1999	Concrete	15.5	8	Inside	Y	Y	Y	Y	N	Y	N
B1	El Trianón	12-31-49.8	86-59-29.8	1999	Plastic	11.4	1	Inside	Y	Y	Y	Y	N	N	N
B2	El Trianón	12-31-58.6	86-59-24.9	2004	Concrete	9.4	0	Outside	N	Y	Y	Y	Y	N	Y
B3	El Trianón	12-31-43.6	86-59-26.8	2004	Concrete	45.8	5	Outside	Y	Y	N	Y	N	N	N
B4	El Trianón	12-31-36.5	86-59-32.2	2004	Concrete	37.5	0	Outside	Y	Y	N	Y	N	N	Y
C1	El Trianón	12-31-41.3	86-59-32.2	1999	Concrete	10.8	8	Inside	Y	Y	Y	Y	N	N	N
C2	El Trianón	12-31-35.6	86-59-33.4	2004	Concrete	8.8	0	Outside	Y	Y	N	Y	N	N	Y
D1	El Trianón	12-31-34.3	86-59-33.9	1999	Concrete	26.0	10.5	Outside	Y	Y	N	Y	N	N	Y
D2	El Trianón	12-31-34.0	86-59-32.6	2004	Concrete	48.9	6	Inside	N	N	Y	Y	N	N	N
E1	El Trianón	12-31-30.7	86-59-34.6	1999	Concrete	19.5	1.5	Outside	Y	Y	Y	Y	N	N	N
F1	El Trianón	12-31-29.3	86-59-31.4	1999	Concrete	50.6	8.5	Inside	N	Y	Y	Y	N	N	N
F2	El Trianón	12-31-28.9	86-59-32.5	1999	Concrete	19.0	4.5	Inside	Y	N	Y	Y	N	N	N
H1	El Trianón	12-31-45.5	87-00-13.9	1999	Concrete	9.7	6	Inside	Y	Y	N	Y	N	N	N
I1	San Gilberto	12-31-59.7	86-57-24.1	2004	Concrete	211.6	7	Inside	Y	Y	Y	Y	N	N	N
I2	Posolteguilla	12-32-15.5	86-58-13.5	2004	Concrete	38.0	2	Inside	Y	Y	Y	Y	N	N	Y
J1	Buenos Aires	12-34-22.4	86-58-56.6	2004	Concrete	63.0	11	Outside	Y	Y	Y	Y	Y	N	N
J2	Buenos Aires	12-34-20.5	86-58-56.8	2004	Concrete	32.0	20	Outside	Y	N	N	Y	N	N	N
J3	Buenos Aires	12-34-26.5	86-59-03.4	2004	Concrete	17.9	16	Outside	Y	Y	Y	Y	N	N	N
K1	El Mojón	12-33-30.2	86-59-49.9	2004	Concrete	1.5	10	Inside	Y	Y	Y	Y	N	N	N
K2	El Mojón	12-33-33.2	86-59-51.9	2004	Concrete	19.5	8.5	Outside	Y	Y	Y	Y	N	N	N
L1	El Mojón	12-33-19.8	87-00-01.5	2004	Concrete	24.0	0	Inside	Y	Y	N	Y	N	N	Y
L3	Posolteguilla	12-32-01.1	86-58-12.2	2004	Concrete	16.9	2	Outside	Y	Y	Y	Y	N	N	N

Table A.2   Water Quality Testing Data

Test ID#	Filter ID#	Source Water DipSlide TTC	MacC	Coliform 1mL	10mL	E. coli 1mL	10mL	Turb GM	Filtered Water Coliform 10mL	100mL	E. coli 10mL	100mL	Turb GM	Stored Water DipSlide TTC	MacCt	Coliform 10mL	100mL	E. coli 10mL	100mL	Turb GM
A1	A1	220	X	86	1164	8	30	0.63	17	137	0	1	0.10			113	TNTC	0	3	1.79
A2	A2	115	24	454	TNTC	106	TNTC	1.56	20	61	2	38	0.36			146	TNTC	13	TNTC	1.00
A3	A3	115	24	97	475	116	236	1.05	615	TNTC	3	TNTC	0.12	32	19	TNTC	TNTC	5	TNTC	0.43
B1	B1	15	6	28	170	1	5	0.31		39		3	0.51	23	23	1700	TNTC	6	37	1.01
B2	B2	62	1	22	168	0	5	1.38		419		2	0.44	90	10	1193	TNTC	76	TNTC	0.74
B3	B3	131	18	390	3180	10	10	4.48		134		5	0.71				TNTC		TNTC	0.86
B4	B4	10	20	94	467	3	16	2.28	23	TNTC	0	13	0.16				894		6	0.32
C1	C1	2	0	20	43	0	0	0.27	157	779	1	0	0.28			509	TNTC	1	3	0.68
C2	C2	55	5	29	141	1	1	0.78	1391	TNTC	1	10	1.37			953	TNTC	2	40	0.54
D1	D1	34	22	222	TNTC	16	300	8.24	45	148	3	15	0.10	1	0	86	140	4	16	0.67
D2	D2	91	94	185	1087	2	15	6.10	25	40	0	0	0.62	150	31	596	TNTC	2	TNTC	0.93
E1	E1	170	30	152	983	2	12	0.38	45	201	3	36	0.23	34	30	289	1680	29	67	0.42
F1	F1	28	11	204	265	1	10	0.72	35	294	0	6	0.27	150	8	197	1248	1	25	0.74
F2	F2	37	16	171	884	0	10	1.95	30	369	0	1	0.31	71	16	896	TNTC	2	22	0.48
H1	H1	54	37	15	232	4	37	1.99	19	146	1	35	0.35	100	9	7	TNTC	4	45	0.51
I1	I1	200	60	505	X	13	X	5.48	47	410	13	125	0.18	158	49	1084	TNTC	10	86	0.92
I2	I2	43	28	2	29	0	0	0.59	12	53	0	2	0.10	300	50	TNTC	TNTC	TNTC	TNTC	0.55
J1	J1	400	90	3000	TNTC	7	36	4.57	24	211	1	6	0.08	5	2	220	2300	3	25	0.60
J2	J2	143	45	519	TNTC	5	19	6.98	2	5	0	0	0.79	144	16	2300	TNTC	135	183	2.80
J3	J3	220	47	4500	X	0	X	2.07	207	1262	0	0	0.19	400	67	106	477	0	0	0.28
K1	K1	59	10	159	813	0	1	3.48	18	149	0	2	0.26	69	2	97	1206	0	1	0.33
K2	K2	23	20	340	1500	20	281	0.78	30	159	4	36	0.04	38	19	913	1700	71	700	0.93
L1	L1	75	16	236	1600	4	14	0.75	13	140	0	1	0.04							
L3	L3	24	16	42	301	0	1	0.58	26	273	0	2	0.24			125	TNTC	10	21	1.01
M1	A1	82	40	8	472	0	0	0.67	500	TNTC	0	0	0.06	TNTC	400	21	TNTC	1	41	0.82
M2	A3	116	25	277	1600	20	75	0.41	164	1359	8	83	0.03	15	16	401	X	68	X	0.29
M3	C1	22	0	5	37	0	1	0.38	31	250	1	14	0.44	96	44	405	962	3	44	0.43
N1	B4	45	6	49	343	0	1	3.69	48	325	2	4	0.02	TNTC	56	611	TNTC	9	125	0.85
N2	D2	208	36	313	2000	0	1	9.43	6	44	0	2	0.20	162	40	145	776	1	17	0.73
N3	B2	89	11	298	TNTC	1	25	1.11	254	TNTC	78	TNTC	0.20	126	16	355	TNTC	215	TNTC	0.77
O1	I1	71	28	341	TNTC	4	65	8.58	4	19	0	1	0.08	127	5	433	TNTC	9	30	0.73
O2	K2	90	15	862	TNTC	130	TNTC	0.83	124	807	44	266	0.04	123	78	47	239	8	119	0.12
O3	J3	97	14	363	TNTC	0	3	3.72	8	22	0	0	0.01	209	3	49	1338	0	8	0.73
P1	A3			X	1400	27	176	0.90	219	1601	8	98	0.51			438	TNTC	21	247	0.53
P2	B4			495	TNTC	4	33	4.32	60	439	0	5	0.04			981	TNTC	4	24	0.53
P3	D2			14	74	0	0	0.82	12	107	0	3	0.04							
Q1	A1			1630	TNTC	1	1	0.85	19	109	0	1	0.10			X	2000	X	11	0.55
Q2	C1			X	200	X	1	0.46	332	958	2	10	0.13			3000	TNTC	0	3	0.34
Q3	B2			248	1129	4	11	0.87	223	1050	108	622	0.17			278	1200	183	800	0.42
R1	I1			463	TNTC	17	85	13.91	0	7	0	0	0.08			1314	TNTC	78	572	0.72
R2	K2			799	TNTC	564	TNTC	1.48	135	703	117	924	0.09			133	732	71	496	0.11
R3	J3			X	TNTC	201	TNTC	2.59	7	35	0	0	0.05			443	TNTC	3	X	0.54

TNTC = too numerous to count; X = unusable results; underlined = estimation; blank = test not performed.

Table A.3   Demographic Data

ID#	Age	Gender	Education	Employment	Illit.	ID#	Age	Gender	Education	Employment	Illit.
A1	53	M	Primary	Landowner		H1	14	F	Primary	None	Y
A1	53	F	Primary	None		H1	24	F	Primary	None	
A1	20	F	High School	Teacher		H1	7	M	Primary	None	
A1	14	F	Basic	Student		H1	5	F			
A2	24	F	Primary	Vendor		I1	43	M	Primary	Landowner	
A2	37	M	Technical	Technician		I1	43	F	Primary	None	
A2	13	M	Primary	Student		I1	22	M	None	Farmhand	Y
A3	67	F	Primary	None	Y	I1	18	M	Primary	Farmhand	
A3	41	M	Primary	Farmhand		I1	16	M	Primary	None	
B1	55	M	None	Farmhand	Y	I1	14	F	Primary	Student	
B1	52	F	Primary	None		I1	12	F	Primary	Student	
B1	24	M	High School	Vendor		I2	52	M	Technical	Technician	
B1	20	M	High School	Vendor		I2	95	M	None	None	Y
B2	78	M	Primary	Landowner		I2	46	F	Primary	Vendor	
B2	59	F	None	None	Y	I2	58	F	Primary	None	
B2	27	M	Technical	Farmhand		I2	49	F	Basic	None	
B2	22	M	None	Farmhand	Y	J1	60	M	None	Farmhand	Y
B2	21	M	Primary	Farmhand		J1	65	F	Primary	None	
B3	52	M	High School	Landowner		J1	21	F	Technical	Technician	
B3	46	F	Primary	None		J1	48	F	Primary	Domestic	
B3	64	F	None	None	Y	J1	14	F	Basic	Student	
B3	23	M	Primary	Farmhand		J1	8	F	Primary	Student	
B3	21	M	Primary	Farmhand		J2	48	M	None	Vendor	Y
B3	15	M	Primary	Farmhand		J2	49	F	Primary	None	
B3	9	M	Primary	Student		J2	19	F	None	None	
B3	42	M	Primary	Farmhand		J2	24	F	Primary	None	
B4	33	M	Basic	Farmhand		J2	13	F	Basic	Student	
B4	32	F	Basic	None		J2	12	M	Primary	Student	
B4	14	F	High School	Student		J2	9	F	Primary	Student	
B4	10	M	Primary	Student		J2	11	F	Primary	Student	
B4	7	F	Primary	Student		J3	40	M	Primary	Farmhand	
C1	53	M	None	Landowner	Y	J3	45	F	Primary	Domestic	
C1	39	F	Primary	None		J3	11	F	Primary	Student	
C1	22	F	Basic	None		K1	28	M	Primary	Farmhand	
C1	18	M	Basic	Student		K1	30	F	Primary	None	
C1	11	M	Primary	Student		K1	7	M	Primary	Student	
C1	6	M	Primary	Student		K1	5	F			
C1	3	M				K1	1	F			
C1	18	M	Primary	Farmhand		K1	54	F	Primary	None	
C2	30	M	Basic	Transportation		K1	19	M	Primary	Farmhand	
C2	30	F	High School	None		K2	52	M	Primary	Landowner	
C2	10	F	Primary	Student		K2	53	F	Primary	None	Y
C2	5	M	Primary	Student		K2	14	M	Basic	Student	
C2	1	M				K2	24	F	Primary	Domestic	
D1	55	M	Primary	Landowner		K2	4	F			
D1	50	F	Primary	None		L1	76	F	Primary	None	
D1	22	F	Basic	None		L1	35	F	Primary	None	
D1	19	M	Basic	Farmhand		L1	17	M	Basic	Farmhand	
D1	10	F	Primary	Student		L1	13	M	Basic	Student	
D1	6	F	Primary	Student		L3	48	F	Technical	None	
D1	1	M				L3	26	M	Technical	Technician	
D2	39	M	Primary	Landowner		L3	25	F	High School	Domestic	
D2	17	F	Basic	Student		L3	20	F	High School	Domestic	
D2	14	F	Basic	Student		L3	19	M	High School	Technician	

ID#	Age	Gender	Education	Employment	Illit.	ID#	Age	Gender	Education	Employment	Illit.
D2	10	M	Primary	Student		L3	7	F	Primary	Student	
D2	8	F	Primary	Student		L3	5	F	Primary	Student	
E1	43	M	Primary	Landowner		L3	2	M			
E1	43	F	None	None		L3	0	F			
E1	16	M	Primary	Farmhand		L3	26	F	High School	None	
E1	8	F	Primary	Student		F1*	24	M	Primary	Farmhand	
E1	4	F	Primary	Student		F1*	25	F	Primary	Vendor	
F1	55	M	None	Landowner		F1*	7	F	Primary	Student	
F1	49	F	Primary	Vendor		F1*	4	F	Primary	Student	
F1	13	F	Basic	Student		F1*	35	F	Primary	Domestic	
F1	10	M	Primary	Student		F1*	18	M	Primary	Farmhand	
F1	20	F	High School	Teacher		F1*	15	F	Primary	None	
F2	49	M	None	Landowner		F1*	13	F	Primary	Student	
F2	32	F	Primary	None	Y	D2*	36	M	Primary	Farmhand	
F2	6	M	Primary	Student		D2*	35	F	Primary	None	
F2	4	M				D2*	15	M	Basic	Student	
F2	8	M	Primary	Student		D2*	13	M	Primary	Student	
H1	52	M	Primary	Vendor		D2*	12	F	Primary	Student	
H1	48	F	None	Vendor	Y	D2*	9	M	Primary	Student	
H1	28	M	None	Farmhand	Y	D2*	8	F	Primary	Student	
H1	24	M	Primary	Farmhand		D2*	4	M	Primary	Student	

* = family sharing filter with corresponding ID#.

Table A.4   Water and Hygiene Behaviour Data

ID#	Daily Water Use (L)	Daily Filter Use (L)	Filtered Water Taste	Filtered Water Smell	Filtered Water Clarity	Family Health	Follow-up Training	Filter Cleaning	Cleaning Frequency (days)	Last Cleaning (days)	Storage Containers	Type of Container	Containers Covered	Containers Clean	Distinct from Transfer	Extraction Method	Dist Latrine to House (steps)	Dist Latrine to Well (steps)	Latrine Clean	Overall Hygiene
A1	500	20	/	/	/	+	Y	Top is Dirty	60	15	1	Bucket	N	N	Y	Specific Cup	24	12	Y	Good but Dusty
A2	400	60	+	+	/	+	N	Slow Flow	60	60	1	Bucket	Y	Y	Y	Any Cup	20	25	Y	Good but Dusty
A3	20	20	+	+	+	+	N	Slow Flow	300	300	1	Bucket	Y	N	Y	Any Cup	17	30	N	Generally Poor
B1	200	20	+	+	/	/	Y	Slow Flow	100	100	1	Bucket	Y	Y	Y	Specific Cup	35	20	Y	Good but Dusty
B2	800	20	+	+	+	+	Y	Schedule	60	60	1	Bucket	Y	Y	Y	Any Cup	45	45	N	Generally Poor
B3		40	+	+	+	+	N	Slow Flow	90	100	1	Bucket	Y	Y	Y	Any Cup	15	80	Y	Good but Dusty
B4	100	25	+	+	+	+	Y		100	100	1	Bucket	Y	N	Y	Any Cup	7	7	Y	Good but Dusty
C1	800	40	+	+	+	+	N	Top is Dirty	30	15	1	Bucket	Y	Y	Y	Specific Cup	17	30	Y	Very Good
C2	800	80	+	+	+	/	N	Schedule	30	45	1	Narrow Mouth	Y	Y	Y	Specific Cup	24	24	Y	Very Good
D1	600	30	+	+	+	+	Y	Slow Flow	5	2	2	Bucket	Y	Y	Y	Any Cup	15	26	Y	Good but Dusty
D2	250	80	+	+	+	+	N		90	180	1	Bucket	N	Y	Y	Any Cup	6	45	N	Generally Poor
E1	300	60	+	+	+	+	N	Schedule	2	2	2	Narrow Mouth	Y	Y	Y	Any Cup	20	25	N	Good but Dusty
F1	900	120	+	+	+	+	Y	Schedule	30	8	1	Bucket	N	Y	Y	Specific Cup	25	45	Y	Good but Dusty
F2	40	20	+	+	+	+	Y	Schedule	8	5	1	Bucket	Y	Y	Y	Specific Cup	30	30	N	Generally Poor
H1		40	+	+	+	+	N	Slow Flow	2	2	2	Bucket	Y	N	N	Any Cup	100	100	N	Generally Poor
I1	450	40	+	+	+	+	Y	Schedule	3	2	1	Bucket	Y	Y	Y	Any Cup	45	35	N	Generally Poor
I2		40	/	/	/	+	N	Schedule	100	100	1	Bucket	N	Y	Y	Any Cup	45	40	Y	Good but Dusty
J1	400	80	+	+	+	+	Y	Top is Dirty	4	3	6	Bucket	Y	Y	Y	Any Cup	25	15	Y	Good but Dusty
J2	150	40	+	+	/	+	N	Slow Flow	30	20	1	Bucket	Y	N	Y	Any Cup	15	25	N	Generally Poor
J3	750	60	+	+	+	+	N	Top is Dirty	2	2	2	Bucket	Y	Y	Y	Any Cup	30	30	N	Good but Dusty
K1	450	60	+	/	+	+	Y	Top is Dirty	30	45	1	Bucket	Y	Y	Y	Specific Cup	15	45	Y	Very Good
K2	500	20	+	/	+	+	N	Schedule	15	8	1	Spout Container	Y	Y	Y	Spout	32	15	Y	Good but Dusty
L1	400	60	+	+	/	+	N	Top is Dirty	7	7	1	Bucket	N	Y	N	Any Cup	30	35	N	Good but Dusty
L3	300	100	+	+	+	+	N	Slow Flow	30	2	1	Bucket	Y	Y	Y	Specific Cup	20	90	Y	Good but Dusty

+ better; / the same

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Table A.5   Housing and Infrastructure Data

ID#	# of Rooms	House Wall Material					House Roof Material				House Floor Material			Mechanical Pump	Covered Well	Electricity	Television	Washbasin	Latrine	Wood Stove	Gas Stove	BioGas Generator	Fridge / Freezer	Vehicle	Other
		Plastic	Metal	Wood	Brick	Concrete	Plastic	Wood	Clay	Metal	Earth	Concrete	Ceramic												
A1	3					X				X	X			X	X	X	X	X	X	X		X			
A2	2					X				X			X	X	X	X	X	X	X	X			X		Store
A3	1					X				X	X			X	X	X			X						Shares with A2
B1	2		X	X						X	X			X	X	X	X	X	X	X					
B2	3	X	X							X	X			X	X	X	X	X		X			X		Food Processor
B3	2					X				X		X		X	X	X	X	X	X	X			X		1500 gal tank
B4	2					X				X		X				X	X	X	X	X			X		
C1	4			X		X				X		X		X	X	X	X	X	X	X		X	X		
C2	3					X				X		X		X		X	X	X	X		X				
D1	3			X		X				X	X	X		X	X	X	X	X	X	X			X		
D2	1					X				X	X					X	X	X	X	X					
E1	2					X				X	X	X		X	X	X	X	X	X	X				X	Farm Tractor
F1	5			X		X				X	X	X	X	X		X	X	X	X	X		X	X		Store
F2	2			X		X				X	X	X				X	X	X	X	X					
H1	3	X	X						X		X			X				X	X	X					
I1	1	X		X						X	X					X	X	X		X					
I2	2					X			X		X			X	X	X	X	X	X	X			X		
J1	2					X			X		X							X	X	X					
J2	2		X			X				X	X					X	X	X		X					
J3	1		X			X				X	X					X		X		X					
K1	1	X		X			X				X							X		X					
K2	1				X					X	X			X	X			X	X	X					
L1	2			X				X	X		X			X	X	X	X	X	X	X					
L3	2					X				X		X		X	X	X	X	X	X	X			X		

Table A.6   QA/QC Laboratory Data

	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8	Solution 9
Volume (mL)	500	500	400	400	400	400	400	400	400
Optical density of neat suspension									
Salmonella		1.504		1.087		0.976	0.988	0.988	0.782
E. coli	1.387		1.031		1.144	1.144	0.806	0.806	0.580
E. fecalis	1.117	1.117	0.665	0.665	0.906	0.906	0.481	0.481	0.496
Average TSA plate count from 0.1mL of dilution order 5									
Salmonella		958		687		792	804	804	569
E. coli	595		315		631	631	387	387	272
E. fecalis	229	229	265	265	488	488	185	185	167
Dilution order injected into test solution									
Salmonella		-5		-4		-5	-4	-5	-4
E. coli	-7		-6		-5	-6	-6	-5	-5
E. fecalis	-3	-3	-2	-2	-2	-2	-2	-2	-2
Spiked volume injected into test solution									
Salmonella		0.9		0.9		0.7	0.9	0.7	0.9
E. coli	1.0		1.0		0.6	1.0	1.0	0.6	0.7
E. fecalis	0.9	1.0	0.9	1.0	0.9	1.0	0.9	1.0	0.9
Membrane Filtration Results for E. Coli									
1 mL	0	0	0	0	5	0	0	1	0
1 mL	0	0	1	0	5	3	0	0	0
1 mL	0	0	0	0	6	2	0	2	0
10 mL	X	0	5	0	23	4	1	3	12
10 mL	2	0	10	0	33	2	0	1	6
10 mL	0	0	10	0	28	3	2	6	10
100 mL	9	0	81	0	398	59	21	75	68
100 mL	2	0	76	0	253	56	18	286	145
100 mL	4	0	84	0	349	56	8	312	142
Membrane Filtration Results for Total Coliforms									
1 mL	0	5	0	169	0	2	16	3	32
1 mL	0	3	0	139	0	11	10	2	38
1 mL	0	7	0	168	0	9	63	1	61
10 mL	X	93	0	1107	0	45	258	6	591
10 mL	2	61	0	1418	0	27	401	6	637
10 mL	2	64	0	1256	0	50	408	13	578
100 mL	2	477	0	TNTC	0	682	TNTC	110	TNTC
100 mL	0	779	0	TNTC	0	644	TNTC	380	X
100 mL	1	772	0	TNTC	0	630	TNTC	377	TNTC
DipSlide Results									
MacConkey	0	0	0	5	2	1	2	12	15
MacConkey	0	0	0	4	0	9	3	0	18
MacConkey	0	0	0	6	0	11	1	12	7
TTC Agar	15	17	125	148	164	296	83	58	60
TTC Agar	28	21	123	155	232	225	92	51	39
TTC Agar	24	27	122	160	237	223	35	45	44

TNTC = too numerous to count; X = unusable results

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Table A.7   Volumetric and Gravimetric Data

	Test 1	Test 2	Test 3	Test 4	Test 5
1 mL Pipette	0.9581	1.0870	1.0372	0.9500	0.9800
1 mL Pipette	0.9930	0.9582	1.0655	0.9655	1.0007
1 mL Pipette	1.0050	0.9138	1.0140	0.9812	0.9860
1 mL Pipette	0.9494	0.9180	0.9696	0.9998	0.9669
1 mL Pipette	0.9834	1.0223	0.9520	0.9176	0.9676
10 mL Beaker	11.0164	10.4500	10.3114	10.4274	10.6282
10 mL Beaker	10.0114	10.8472	10.6658	10.6546	10.8402
10 mL Beaker	11.0559	11.0233	10.8468	10.7120	11.0193
10 mL Beaker	10.9117	10.3993	10.6954	10.5650	10.3184
10 mL Beaker	10.6265	10.8271	10.9121	10.8880	10.9500
10 mL Beaker	11.4664	11.2137	10.9492	11.1663	11.0365
10 mL Beaker	10.8690	10.5255	10.9045	10.6076	11.0900
10 mL Beaker	10.2600	10.6402	10.6388	10.3125	10.5111
10 mL beaker	11.1393	10.6180	10.7027	10.7023	10.8561
10 mL Beaker	10.6655	10.3884	10.5818	11.1019	10.8472
10 mL Beaker	10.6177	10.2900	10.6199	10.7422	10.7996
100 mL Reservoir Tube	103.26	102.85	104.30	104.30	
100 mL Reservoir Tube	104.93	103.32	104.60	104.80	

Appendix B: Sample Calculations

Presented in this section are the calculations used in the analysis of the data collected during the BioSand Filter evaluation, including the computation of statistical significance.

B.1 Statistical Significance

The test for Student's t was used to test the null hypothesis that two population means are equal, and to determine the statistical significance of linear correlations. If the p-value, the probability that the difference in means (or the slope of a linear correlation) would happen by chance, is below a specified level of α (typically 0.05 or 0.01) then the null hypothesis can be rejected, and the difference between the population means (or the correlation) is statistically significant. The statistical calculations were performed within Microsoft Excel using the Data Analysis add-in and built-in functions of TTEST() and TINV(), and thus many of the following calculations were not explicitly performed, but are provided for reference only.

B.1.1 Student's t Distribution

The probability density function of Student's distribution is defined by the following:

$$f(t) = \frac{\Gamma(\frac{v+1}{2})}{\sqrt{v\pi} \cdot \Gamma(\frac{v}{2})} \left(1 + \frac{t^2}{v}\right)^{-\left(\frac{v+1}{2}\right)} \tag{5}$$

Where: t is the parameter of the distribution, varying from $-\infty$ to ∞.

v is the degrees of freedom, which is not constrained to the integer domain.

$\Gamma(z)$ is the gamma function, defined by the following infinite integral:

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt \tag{6}$$

The function $A(t|v)$ is the integral of Student's probability density function between $-t$ and t. This is the probability that a value of t less than that calculated from observed data would occur by chance. It has the following expression:

$$A(t|v) = \frac{1}{\sqrt{v} \cdot B\left(\frac{1}{2}, \frac{v}{2}\right)} \int_{-t}^{t} \left(1 + \frac{x^2}{v}\right)^{-\left(\frac{v+1}{2}\right)} dx \qquad (7)$$

Where: t is the parameter of the distribution

v is the degrees of freedom

$B(x, y)$ is the beta function, a finite integral that is related to the gamma function:

$$B(x, y) = \int_{0}^{1} t^{x-1} (1-t)^{y-1} dt = \frac{\Gamma(x) \cdot \Gamma(y)}{\Gamma(x+y)} \qquad (8)$$

The probability that a value of t greater than or equal to that observed would happen by chance is the p-value, and is the complement of the $A(t|v)$ integral:

$$p = 1 - A(t|v) \qquad (9)$$

Values of p that are below a specified level of α (typically 0.05 or 0.01) are considered statistically significant. In this manner, the Student's distribution can be used to determine the statistical significance of any particular values of t and v.

B.1.2   Student's *t*-test

To determine the statistical significance of the difference between the means of two samples, Student's *t*-test was performed to calculate t and the degrees of freedom. Variations of the test exist depending upon whether the sample sizes are equal, and whether the variances within each sample are assumed to be equal. The heteroscadistic variant of the Student's *t*-test (called Welch's *t*-test) was used because the sizes and variances of the two samples being compared were assumed to be unequal. The *t*-value and the degrees of freedom of this test are computed as follows:

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\dfrac{s_1^2}{N_1} + \dfrac{s_2^2}{N_2}}} \tag{10}$$

$$v = \frac{\left(\dfrac{s_1^2}{N_1} + \dfrac{s_2^2}{N_2}\right)^2}{\dfrac{s_1^4}{N_1^2(N_1-1)} + \dfrac{s_2^4}{N_2^2(N_2-1)}} \tag{11}$$

Where: t is the parameter of Student's distribution

v is the degrees of freedom, which is not restricted to the integer domain

$\overline{X_1}$ and $\overline{X_2}$ are the sample means

N_1 and N_2 are the sample sizes

s_1 and s_2 are the sample standard deviations.

The computed values of t and v were then used to determine the statistical significance of the difference between samples as described previously. If the difference in means was found to be statistically significant, then the parameter used to separate the study population into the two samples is of importance to the study. Otherwise, the parameter is not important, and the samples can be aggregated for subsequent analysis.

B.1.3   Linear Correlation

The correlation between two continuous variables was measured using the Pearson product moment correlation coefficient. This value is strictly between the values of −1 and 1; the closer the absolute value is to 1 indicates a stronger correlation, and the sign indicates a positive or negative correlation. The correlation coefficient is calculated as follows:

$$r = \frac{\sum_{i=1}^{N}(X_i - \overline{X})(Y_i - \overline{Y})}{(N-1)s_X s_Y}$$ **(12)**

Where: r is the correlation coefficient

X_i and Y_i are the ith value of N in the series of X and Y respectively.

$\overline{X}$ and $\overline{Y}$ are the sample means.

s_X and s_Y are the sample standard deviations.

The coefficient of determination (R^2) is equal to the square of the correlation coefficient. This coefficient is a measure of the amount of variance in the Y variable that can be accounted for by changes in X and the linear relationship between X and Y. The value of R^2 is strictly between 0 and 1, with 1 representing a perfect linear relationship and 0 representing no relationship.

Computation of the correlation coefficient or the coefficient of determination assumes that both series are normally distributed. Any series exhibiting a log-normal distribution are thus logarithmically transformed prior to computing the correlation.

The statistical significance of a correlation is determined by testing the null hypothesis that the slope of the regression line is equal to zero, representing complete random scatter and hence no correlation between the variables. This is done by computing the t-value using the following equation.

$$t = r\sqrt{\frac{N-2}{1-r^2}}$$ **(13)**

Where: t is the parameter of Student's distribution.

r is the correlation coefficient between the two variables.

N is the number of pairs of X and Y variables.

The value of t and the degrees of freedom (N-2) are used to compute p, the statistical significance of the correlation. It should be noted that for large N, t becomes large and thus even

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small values of r become statistically significant. For instance, if $N = 40$ a correlation coefficient of $r = 0.3$ is statistically significant at the $\alpha = 0.05$ level, even though R^2 is only 0.09. This is because the correlation indicates that the variables are dependent but the relationship is not direct as there are contributions from other factors.

B.1.4 Linear Regression

When a correlation is statistically significant, the linear regression coefficients can be used to describe the relationship between the two variables using the linear model $Y = a + b{\cdot}X$. The slope and intercept of the trend line through the data are computed using the least squares method, as follows:

$$b = \frac{\sum_{i=1}^{N}(X_i - \overline{X}) \cdot (Y_i - \overline{Y})}{\sum_{i=1}^{N}(X_i - \overline{X})^2} \qquad (14)$$

$$a = \overline{Y} - b \cdot \overline{X} \qquad (15)$$

Where: a and b are the regression coefficients (intercept and slope respectively)

X_i and Y_i are the ith value of N in the series of X and Y respectively.

$\overline{X}$ and $\overline{Y}$ are the sample means

B.2   BioSand Filter Evaluation Calculations

B.2.1   Calculation of Flow Rate

One of the variables collected during the household visits was the hydraulic flow rate through the filter. This was determined by using a stop watch to measure the time (in seconds) required to fill a 250 mL cup with filtered water immediately upon introducing 20 L into the top reservoir of the BioSand Filter. This flow-time was converted to a volumetric flow rate in L/min by the following calculation:

$$Q = \frac{0.25\text{L}}{T} \cdot \frac{60\text{s}}{\text{min}}$$

<div align="right">(16)</div>

Where: Q is the volumetric flow rate in L/min

T is the time, in seconds, required to fill 0.25L

According to Darcy's Law, the flow through a media is controlled by the permeability, and the media with the lowest permeability is the limiting constraint on the flow rate. In the case of the BioSand Filter, the lowest permeability is exhibited at the top of the sand where the biological layer is developed. Because BioSand Filters exist in different shapes and sizes, a more accurate representation of the flow through the filter is the normalization of the volumetric flow rate by the cross-sectional area of the top of the sand layer. In a traditional slow sand filter, where the influent water flow rate is continuous and held relatively constant, this is termed the filter loading rate. A BioSand Filter is operated intermittently, where a 20 L bucket of water is applied nearly instantaneously, and thus the filter loading rate is not defined. Rather, the normalization of the volumetric flow rate by the cross-sectional area is termed the filter flow-through rate, and is calculated as follows:

$$q = \frac{Q}{A} \cdot \frac{60\,\text{min}}{\text{hour}} \cdot \frac{\text{m}^3}{1000\text{L}}$$

<div align="right">(17)</div>

Where: q is the filter flow-through rate in m^3/m^2/hour or m/hour

Q is the volumetric flow rate in L/min

A is the cross-sectional area of the filter at the top of the sand, in m^2.

It should be noted that both the volumetric flow rate and the filter flow-through rate were measured and reported at their peak, after the addition of the 20 L volume of water when the head over the media is the highest. As the water drains from the filter, the head over the media decreases, and thus the flow is steadily decreased.

B.2.2   Calculation of Microbial Concentration

The membrane filtration procedure was carried out twice on every water sample at two different volumes: 1 mL and 10 mL for source water and 10 mL and 100 mL for filtered and stored water. The estimation of the actual concentration in the water sample is a function of the two results. The QA/QC analysis performed in the laboratory quantified the expected error associated with the MF plate count. It was also determined that the expected error can be minimized through the selection of the plate count used to estimate the actual concentration, by targeting a plate count between the control points of 15 and 150 CFU.

The pseudocode provided below selectively identifies the plate count to be used in estimating the actual concentration so as to minimize the expected error for a water sample tested at 100 mL (large plate count) and 10 mL (small plate count). For the samples tested at 10 mL and 1 mL, the final result must be multiplied by 10 to provide CFU/100 mL. The pseudocode also assigns values of 0.5 to any outcome that would otherwise be 0 for the purpose of subsequent analysis.

```
if both plate counts are numeric // i.e. not TNTC
     if the large plate count is between 15 and 150
          if the small plate count is between 15 and 150
               average of large and 10x small count plate counts
          else
               large plate count
     else if the small plate count is between 15 and 150
          10x small plate count
     else if the large plate count is smaller than 15
          max of large plate count and 0.5 // catch possible 0 values
     else if small plate count is greater than 150
          10x small plate count
     else // neither count is in the desired range – choose the one closest to the limit
          if large plate count / 150 < 15 / small plate count
               large plate count
          else
               10x small plate count
else // use the available numeric plate count if possible
     if large plate count is numeric
          max of large plate count and 0.5
     else if small plate count is numeric
          10x max of small plate count and 0.5
     else
          error // TNTC or otherwise unusable results
```

B.2.3   Geometric Mean and Geometric Standard Deviation

The microbial and turbidity results from the water testing component of the BioSand Filter

evaluation were found to vary over several orders of magnitude. The distribution of each series

approximated a log-normal distribution, and therefore each series was logarithmically

transformed prior to performing any statistical analysis. The geometric mean and geometric

standard deviation were reported, which are the exponentiation (antilog) of the algebraic mean

and standard deviation of the logarithmically transformed series. The base of the logarithmic transformation can be in any base (i.e. e, 10, etc.) provided that both the log and antilog functions use the same base.

$$\overline{\log X} = \frac{1}{N}\sum_{i=1}^{N}\log X_i \tag{18}$$

$$GM = \text{antilog}\left(\overline{\log X}\right) \tag{19}$$

$$GSD = \text{antilog}\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\log X_i - \overline{\log X}\right)^2}\right) \tag{20}$$

Where: GM is the geometric mean of the series

GSD is the geometric standard deviation of the series

X_i is the ith value of N in the series of X, and log X_i is its log transform.

When used to describe the characteristics of a log-normal distribution, the GSD is a multiplicative (and divisive) factor of the GM. In a perfect log-normal distribution, approximately 68% of the data are found between GM÷GSD and GM×GSD, and approximately 95% of the data are found between GM÷GSD^2 and GM×GSD^2.

B.2.4 Calculation of Log Reduction and Filtration Efficiency

The filter efficiency was computed as a log reduction (LR) from the source contaminant metric to the filtered metric. The LR is a more useful representation of filter efficiency than percentage removal for statistical analysis because it includes the logarithmic transformation of the log-normally distributed water quality results, and therefore will better follow a normal distribution. Furthermore, the additive property of LR values makes them more appropriate than percent removal for using linear statistical correlation models to determine trends in the data. The equation for LR, given a source value of S and filtered value F, and its relationship to the percentage removal efficiency (Eff) is:

$$LR = \log\left(\frac{S}{F}\right) = -\log(1 - Eff) \tag{21}$$

$$Eff = \frac{S - F}{S} = 1 - 10^{-LR} \tag{22}$$

Where: LR is the log reduction

Eff is the decimal representation of the percent removal efficiency

S is the source metric

F is the filtered metric

Nine houses were selected for a total of three household visits, with a series of water quality tests performed each time. The geometric mean was computed between the three independent tests from each sample location (source, filtered, stored) and this value was used to represent a single data point for subsequent calculations. For example, the LR value for a particular household was computed from the geometric mean source water quality and geometric mean filtered water quality. This approach is justified because it is numerically equivalent to the arithmetic mean of the LR computed from each household visit, by the following identity:

$$\frac{1}{3}\left(\log(S_1 / F_1) + \log(S_2 / F_2) + \log(S_3 / F_3)\right) = \log\left(\frac{\sqrt[3]{S_1 \cdot S_2 \cdot S_3}}{\sqrt[3]{F_1 \cdot F_2 \cdot F_3}}\right) \tag{23}$$

Where: S_i and F_i are the source and filtered metric from each visit i

The result of the cubic root function is the geometric mean of the three values.

B.2.5 Correlation between Filtration Efficiency and Source Concentration

A statistically significant linear correlation was detected between the filtration efficiency and the logarithm of the source concentration. This relationship was used to develop a predictive model for the change in the filtered water quality as a result of changes in the source water quality. The development of the model is as follows:

Define S_1 as a metric of source contamination, and S_2 as a higher level of contamination from the same source. The corresponding log reductions (LR_1 and LR_2) that yield the filtered metrics (F_1 and F_2) are related as follows, from Equation (21):

$$\log(F_1) = \log(S_1) - LR_1 \tag{24}$$

$$\log(F_2) = \log(S_2) - LR_2 \tag{25}$$

Applying the linear correlation, a change in $\log(S)$ will result in a linear change in LR by some linear coefficient b:

$$LR_2 - LR_1 = b \cdot \left(\log(S_2) - \log(S_1)\right) \tag{26}$$

Subtracting Equation (24) from Equation (25) and substituting Equation (26) yields:

$$\log(F_2) - \log(F_1) = \log(S_2) - \log(S_1) - b \cdot \left(\log(S_2) - \log(S_1)\right) \tag{27}$$

Rearranging yields the following model as presented in Chapter 2, with b replaced by β, the correlation coefficient computed between the log of source contamination and the log reduction across the filter.

$$\frac{F_2}{F_1} = \left(\frac{S_2}{S_1}\right)^{1-b} \tag{28}$$

B.3   QA/QC Calculations

B.3.1   Preparation of Test Solutions

The calculation of the number of organisms in the spiked test solutions was a matter of accounting for the number of ten-fold dilutions that were performed and correcting for the volumes. The final calculation is shown below:

$$C = \frac{X}{w} \cdot \frac{v}{V} \cdot 10^{m-n} \cdot \frac{100 \cdot (1\,\mathrm{mL})}{(100\,\mathrm{mL})} \qquad \textbf{(29)}$$

Where: C is the spiked organism concentration, in CFU/100mL

X is the average number of colonies counted on the TSA plates (CFU)

w is the volume spread onto the TSA plates for enumeration (0.1mL)

v is the volume injected into the test solution (mL)

V is the volume of the test solution (mL)

m is the dilution order spread onto the TSA plates for enumeration (5)

n is the dilution order of the volume injected into the test solution.

B.3.2 Coefficient of Variation

The coefficient of variation was used as the measure of error in the QA/QC laboratory work. The coefficient of variation is the normalization of the standard deviation of the mean, and is therefore appropriate for comparisons of the variation between series that differ by orders of magnitude.

$$CV = \frac{s_X}{\overline{X}} \qquad \textbf{(30)}$$

Where: CV is the coefficient of variation

$\overline{X}$ is the sample mean and s_X is the sample standard deviation.

Computation of the coefficient of variation assumes that the data within each series is normally distributed. In the case of the QA/QC work, the coefficient of variation was applied in two cases: to the three samples taken at the same volume of the same test solution, and then between the volume-normalized averages of the adjacent volumes (1 and 10 mL, and 10 mL and 100 mL) of the same test solution. Each of these series was assumed to be normally distributed.

When the sample consists of only two data points X_1 and X_2, the computation of the coefficient of variation simplifies to the following:

$$CV = \sqrt{2} \frac{|X_1 - X_2|}{X_1 + X_2} \qquad \textbf{(31)}$$

The limiting value for the two-point coefficient of variation, when the values of X_1 and X_2 differ by several orders of magnitude, is $\sqrt{2}$ or approximately 141%. This is also the coefficient of variation for an expected value for X of 0.5, when a set of two tests yields results of 0 and 1.

B.3.3   Bounding curve

A bounding curve on the coefficient of variation versus plate count means was developed from the laboratory data. The form of the curve was assumed to be parabolic on the log-x scale, described by the following equation:

$$y = a \cdot (\log x)^2 + b \cdot (\log x) + c \qquad \textbf{(32)}$$

Where: y is the maximum expected coefficient of variation

                x is the plate count, independent of the volume tested.

                a, b and c are the coefficients of the bounding curve.

Visual inspection suggested that the bounding curve agrees with the limit for an expected value of X of 0.5, and should therefore pass through the point $(0.5, \sqrt{2})$, as suggested above. Through least-squares methods and inspection of the uppermost data points from the set, the coefficients of the bounding curve were determined. The laboratory data and the bounding curve are plotted in Figure B.1.
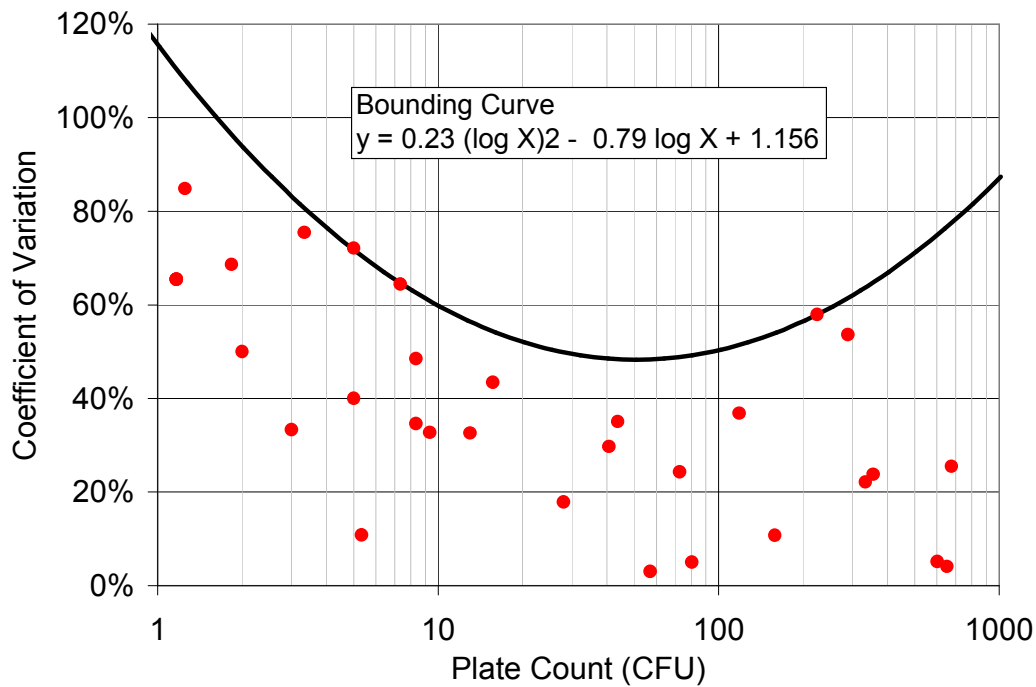
Figure B.1   Bounding Curve for Coefficient of Variation versus Plate Count Mean

Because the lack of effect of the actual volume filtered on the coefficient of variation, this boundary curve is assumed to be valid for any filtered volume. The graphic in Figure 3.7 displays the bounding curve for the filtered volume of 100 mL, 10 mL and 1 mL. The intersections of these curves (approximately 15, 150 and 1500) define the breakpoints used in the computation of the organism concentration used in the pseudocode described above.

Appendix C: Questionnaire

UBC The University of British Columbia **Department of Civil Engineering**	**Questionnaire of Behavioural and** **Socioeconomic Determinants**

Use and Performance of BioSand Filters in Posoltega, Nicaragua

(Original in Spanish) This questionnaire is a part of the indicated study being conducted by Jason Vanderzwaag of the Department of Civil Engineering at the University of British Columbia. This study consists of taking water samples of filtered and unfiltered water, and an interview of a family representative regarding family demographics, water and sanitation practices, and use of the BioSand Filter. By responding to the questions of the questionnaire, the interviewee is consenting to their participation in the study. To maintain the confidentiality of study participants and their families, all identifiable information will be recorded on this top sheet which will be removed from the rest of the questionnaire and kept in a separate file. This information has been provided to the interviewee prior to their participation in the study, as witnessed by:

Witness Signature _____   Date _____

1   Interview Information

  1.1   Date of Interview_____

  1.2   Interview ID Number _____

  1.3   Address _____

  1.4   GPS Coordinates _____

2   Household Members

	Names		Surnames	
ID	**First**	**Second**	**First**	**Second**

3 Household Demographics

3.1   Age and Gender of Household Members

ID	Age	Gender

3.2   Using *only* the ID numbers draw a family-tree diagram indicating how persons within the household are related. Also, indicate the position of the interviewee, and the individual normally responsible for filtering water.

3.3   Identify the education levels of household members:

ID	Education Level						Literacy	
	Preprimary	Primary	Basic	Div/Bach	University	Post-Grad	Lit.	Illit.

3.4   Type of Employment / Daily Activities of Family Members

ID	Farming Own Land	Farm Worker "Obrero"	Teacher	Vendor / Shopkeeper	Government / Public Servant	Transportation (Taxi / Bus)	Student	Not Employed Outside Home	Working outside of Community*

* i.e. Managua, other cities, other countries (specify).

4   Water Questions

4.1   What are your sources of water?

   a) Well
   b) Piped
   c) Canal, river or stream
   d) Rain
   e) Other _____

4.2   What is your favourite source

   a) Well
   b) Piped
   c) Canal, river or stream
   d) Rain
   e) Other _____

4.3   Why do you like it better?

   a) Closer
   b) Better Quality (Taste, Odour, Colour)
   c) Other _____

4.4   How much water do you use every day? (Buckets) _____

4.5   How long does it take to get water? _____

4.6   Do all family members drink filtered water? _____

4.7   What water do household members drink when they are not at home?

ID	Purchase Bottled Water	Canal, River, Stream	Well or Pump (Unfiltered)	Filtered Water From Home	Other

5   BioSand Filter Questions

5.1   How long have you had the filter? _____

5.2   Did any household members receive training on the use of the BioSand Filter when it was originally installed? (ID's)_____

5.3   Did any household members receive follow-up training anytime after the filter was originally installed? (ID's) _____

5.4   Do other families share the use of the BioSand Filter? (#)_____

5.5   How much water is filtered every day? (# & size of buckets) _____

5.6   What are all the purposes that you use filtered water for?

    a) Drinking
    b) Food Preparation
    c) Bathing and Washing Hands
    d) Other _____

5.7   Do you do anything with the source water before you put it into the filter?

    a) Let it Settle
    b) Add a coagulant
    c) Pour through a cloth or other pre-filter
    d) Other _____

5.8   How does the filtered water compare to the unfiltered water by the following categories?

	Better	**Worse**	**Same**	**Comments**
Taste				
Smell				
Appearance				

5.9   Since you started using the filter, do you think that your family's health has improved, stayed the same, or become worse?

    a) Better
    b) Worse
    c) About the Same
    Comments: _____

5.10   Does the filter produce enough clean water for the entire household?_____

5.11   How do you know when it is time to maintain the filter? (by washing the top sand)

   a) When the flow is very slow
   b) When the top of the filter looks dirty
   c) On a regular schedule
   d) Other _____

5.12   How often is this maintenance performed?_____

5.13   How long ago was the dirty sand last cleaned?_____

5.14   After maintaining the filter, do you use water from a different source, or do anything different with the treated water? _____
_____

5.15   Have you ever had any problems with the filter?

   Comments: _____

5.16   Do you ever require help to fix or maintain the filter?

   Comments: _____

5.17   Do you like the filter? _____

5.18   Would you recommend the filter to others? _____

5.19   Do you do anything with the water after it has gone through the filter?

   a) Store in containers (ask 5.20)
   b) Apply further treatment (ask 5.21 to 5.24)
   c) Nothing – use immediately
   d) Other _____

5.20   What method is used to extract water from the storage containers?

   a) Tap or spout
   b) Dip with a designated cup or ladle
   c) Dip with any cup or ladle
   d) Pour directly from the container
   e) Other _____

5.21   What do you use for subsequent treatment?

   a) Commercial Chlorine
   b) Bleach
   c) Solar Disinfection
   d) Other _____

5.22   What do you use this treated water for?

a) Drinking
b) Food Preparation
c) Bathing and Washing Hands
d) Other _____

5.23   How does the treated water compare to the filtered water by the following categories?

	Better	Worse	Same	Comments
Taste				
Smell				
Appearance				

5.24   Is it easy to use chlorine / treat the water after filtration?_____

6   Sanitation and Hygiene Questions

6.1   Where does the family defecate?

a) Toilet
b) Latrine
c) Bucket (skip next question)
d) In the open (skip next question)
e) Canal (skip next question)
f) Other _____

6.2   Do you share with other households?

6.3   What do you do with garbage?

a) Burned
b) Latrine
c) Municipal collection
d) Buried
e) Fed to animals
f) Other _____

The interview is now over. Thank the interviewee for their participation. Proceed to the

recording of observations on the following pages.

Interview ID#_____

7 Housing Observations
7.1 Living Arrangements

a) Single-family dwelling
b) Multi-family dwelling
c) Other _____

7.2 Construction Materials

Item	Walls	Roof	Floor
Wood Sticks			
Concrete & Block			
Brick & Stone			
Adobe			
Sheet Metal			
Earth			
Clay / Ceramic			
Thatch			
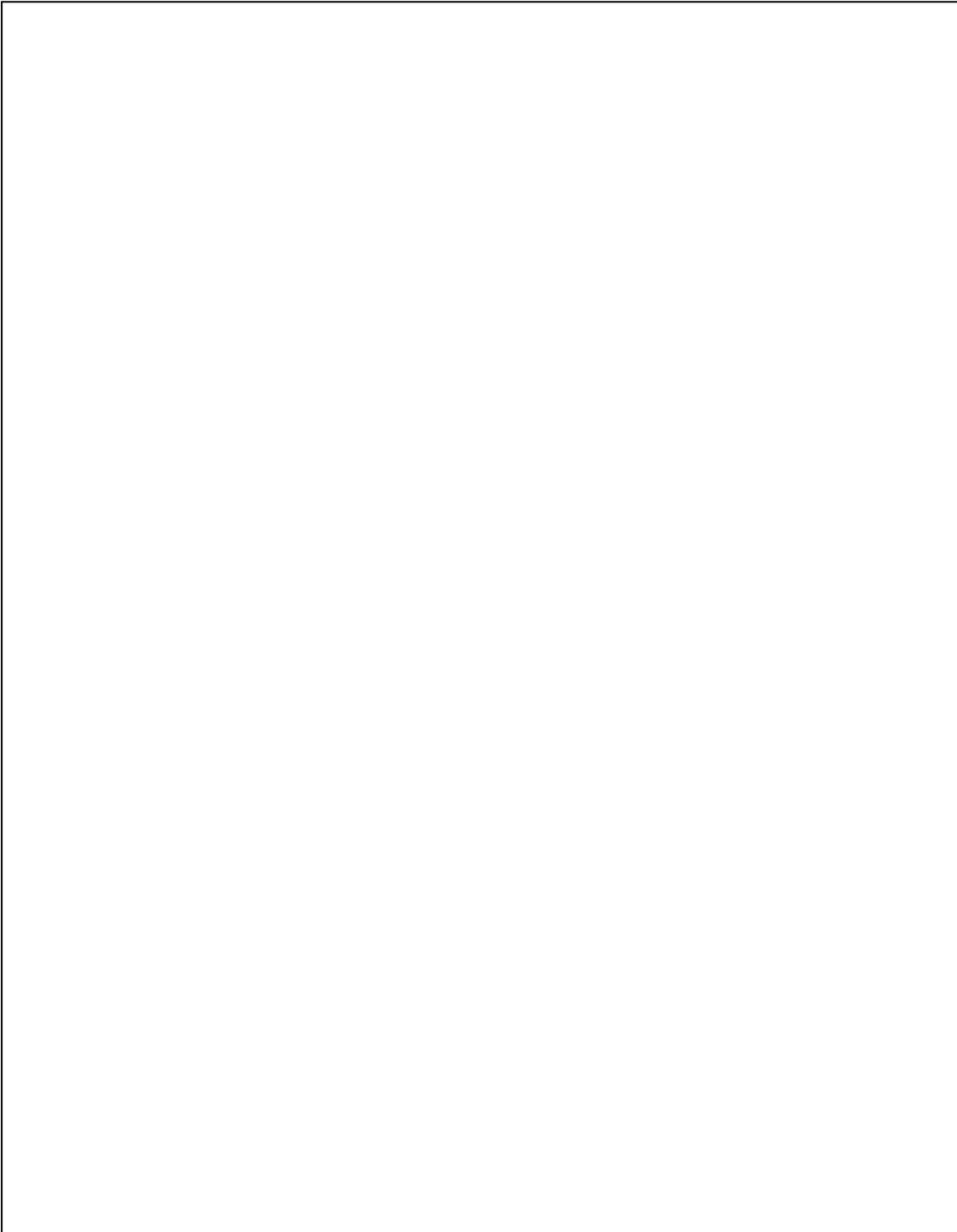
7.3 Rooms in the House (#)

a) Bedrooms _____
b) Kitchen
c) Living Room / Common Room
d) Bathroom
e) Other _____

7.4 Infrastructure in the House (underline all that apply)

a) Well (describe) _____
b) Piped Water / Water Storage System
c) Sewage / Drainage Connection
d) Electricity
e) Television
f) "Pilas" Laundry facilities / Laundry Machine
g) Latrine / Running Toilet / Pit
h) Wood Stove / Gas Stove / BioGas Stove / Electric Stove
i) Refrigerator / Freezer
j) Car / Motorbike / Other_____
k) Other _____

7.5   Provide a sketch of the house / lot, including locations of: BioSand Filter, well / water sources, cooking facilities, laundry facilities, toilet facilities, etc.

10 Sanitation Assessment (Say: "May I see your toilet / latrine?")

10.1   Where is the toilet located?

    a) In house
    b) In yard
    c) Outside of yard - private
    d) Outside of yard - public
    e) No toilet

10.2   How far is the sanitation facility from: (# of steps)

    a) House_____
    b) Well / Pump_____
    c) Creek, river or other source_____
    d) BioSand Filter _____

10.3   Is the toilet facility clean? _____

11 Hygiene Assessment (Say: "May I see where you wash your hands?")

11.1   Location of place used to hand wash most frequently

    a) At or near sanitation facility
    b) At or near kitchen
    c) Inside living quarters
    d) Outside in yard
    e) "Pilas" washbasin
    f) Other _____

11.2   Are the following present?

Item	Present?	Comments
Water		
Soap		
Towel		

11.3   Evaluation of general hygiene of house

    a) Very good household hygiene
    b) Good household hygiene, but dusty
    c) Generally poor household hygiene
    d) Very poor household hygiene

11.4   Comments _____

Appendix D: Behavioural Research Ethics Board Certificate of Approval

<table>
<tr>
<td colspan="3">
The University of British Columbia
Office of Research Services
Behavioural Research Ethics Board
Suite 102, 6190 Agronomy Road, Vancouver,
B.C. V6T 1Z3
</td>
</tr>
<tr>
<td colspan="3" align="center"><h1>CERTIFICATE OF APPROVAL - FULL BOARD</h1></td>
</tr>
</table>

PRINCIPAL INVESTIGATOR:	INSTITUTION / DEPARTMENT:	UBC BREB NUMBER:
James W. Atwater	UBC/Applied Science/Civil Engineering	H07-01885

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:

Institution	Site
N/A	N/A

Other locations where the research will be conducted:

subject's home

CO-INVESTIGATOR(S):
Karen H. Bartlett
Jason Vanderzwaag

SPONSORING AGENCIES:
N/A

PROJECT TITLE:
Use and Performance of the BioSand Filter in Posoltega, Nicaragua

REB MEETING DATE:	CERTIFICATE EXPIRY DATE:
December 13, 2007	**December 13, 2008**

DOCUMENTS INCLUDED IN THIS APPROVAL:	DATE APPROVED: **January 4, 2008**

Document Name	Version	Date
Protocol:		
Proposal	N/A	October 20, 2007
Questionnaire, Questionnaire Cover Letter, Tests:		
Questionnaire	N/A	October 20, 2007

The application for ethical review and the document(s) listed above have been reviewed and the procedures were found to be acceptable on ethical grounds for research involving human subjects.

Approval is issued on behalf of the Behavioural Research Ethics Board
and signed electronically by one of the following: