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Community and Household Management Strategies for Water Supply and Treatment in Rural and Peri-urban Areas in the Developing World

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Community and Household Management Strategies for Water Supply and Treatment in Rural and Peri-urban Areas in the Developing World

by

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DEDICATION

This is dedicated to the two most important people in my life: my mother and father.

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ABSTRACT

Eighty percent of the 780 million people worldwide that access water from an unimproved source live in rural areas. In rural areas, water systems are often managed by community based organizations and many of these systems do not provide service at the designed levels. The Sustainability Analysis Tool developed in Chapter 2 can inform decision making, characterize specific needs of rural communities in the management of their water systems, and identify weaknesses in training regimes or support mechanisms. The framework was tested on 61 statistically representative geographically stratified sample communities with rural water systems in the Dominican Republic. The results demonstrated the impact that long term support by outside groups to support community management activities can improve sustainability indicators, including financial sustainability which is a significant issue throughout the world.

When analyzing the financial sustainability of water systems, it is important to consider all life-cycle costs including the expenditures made by households. Chapter 3 analyzes financial and economic expenditures on water services in 9 rural and peri-urban communities in Burkina Faso. Data from household and water point surveys were used to determine: socio-economic status, financial and economic expenditures, and service levels received by each household. In Burkina Faso recurrent financial and economic expenditures on water service ranged between US$5 and US$9.5 per person per year, with cumulative costs approximately US$19.5 per person

per year. The average expenditures on water in Burkina Faso were well above the affordability threshold used by World Bank demonstrating the need to improve subsidies in the water sector.

The sustainability of water supply systems and the ability to ensure the health benefits of these systems is also influenced by the deficiencies in sanitation infrastructure. Unimproved sanitation can be a source of water contamination and a risk factor in water related disease. Furthermore, the effective management of community water supply infrastructure is not a sufficient condition for ensuring water quality and eliminating health risks to consumers. As a result water treatment technologies, such as ceramic water filters (CWFs), implemented and managed at the household level and combined with safe storage practices are proposed as a means of reducing these risks.

The performance of CWFs in laboratory settings has differed significantly from field studies with regard to microbial treatment efficacy and also hydraulic efficiency. Chapter 4 presents a 14 month field study of two locally manufactured CWFs conducted in a rural community in the Dominican Republic. Each of the 59 households in the community received one filter. The CWFs in this study performed poorly with regard to water quality and hydraulic performance. Focus group meetings and household survey suggests that flow rate is a major issue for user acceptability. To address the user concerns Chapter 5 presents two mathematical models for improving the hydraulic performance for the frustum and paraboloid designs. The models can be used to predict how changes in user behavior or filter geometry affects the volume of water produced and therefore can be used as tools to help optimize filter performance.

1 INTRODUCTION

Significant progress has been made towards achieving the Millennium Development Goals (MDGs) for ending extreme poverty and hunger, providing primary education and basic healthcare, combating infectious disease and ensuring environmental sustainability (UN 2012). Significant progress has been made with regard to MDG Target 7c- to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation. Although advances are being made, many individuals who make up the most vulnerable populations are failing to be reached. The number of people accessing drinking water from improved sources[1] has increased from 77 percent in 1990 to 89 percent in 2010, and is expected to reach 92 percent by the target year of 2015, exceeding the goal by 4 % (UN 2012). However, there are still areas of the world that lag behind with regard to meeting the MDG target for water.

In all regions of the developing world, rural water coverage lags behind urban coverage and today eight out of ten people who lack access to an improved drinking water source live in rural areas (UN 2011). Disaggregating data from sub-Sahara Africa by wealth shows that the poorest 20 percent of urban dwellers still enjoy better access than 80 percent of rural inhabitants (UN 2011). With regard to sanitation, the disparity between rural and urban and rich and poor is even greater. The global target for sanitation coverage is 77 percent while currently only 63 percent of the population has access to improved sanitation facilities (UN 2012). Although the

[1] An improved water source is defined by the World Health Organization (2011) as water provided through household connections, public standpipes, boreholes, protected dug wells, protected springs, or rainwater collections. Unimproved sources are those that are unprotected or vendor provided (tanker truck or bottled water).

gap in sanitation coverage between urban and rural areas is shrinking, in developing regions an urban resident is 1.7 times more likely to use an improved facility than someone in a rural area, a fact which puts rural areas at a distinct disadvantage with regard to water related diseases (UN 2011). Lack of access to safe water and sanitation infrastructure along with proper hygiene practices is behind only “childhood underweight” as the leading risk factor for disease in developing countries (Fry et al. 2013). The disease burden of water, sanitation, and hygiene (WASH) related illnesses is manifested annually in 4 billion cases of diarrhea and 1.9 million deaths and is predominantly bourn by children under the age of 5 years (WHO 2010).

The deficiencies in sanitation infrastructure worldwide and the slow progress towards universal sanitation coverage, which at current rates would not be attained until 2100, also may pose a significant threat to water supplies. Currently 949 million people practice open defecation and another 425 million used shared sanitation facilities (UN 2012) which may be unhygienic or have associated accessibility issues (e.g.- no access at night). Proper disposal of fecal matter and adequate hygiene are important factors in reducing the occurrence of water related disease. Considering that 187 million people currently use untreated surface water as their primary source of drinking water (UN 2012), the practice of open defecation and universal access to hygiene sanitation facilities is of significant concern. Therefore the effective management of these water supplies and the appropriate use of water treatment technologies will be important for minimizing the risk of water related diseases.

1.1 Water Supply

Experiences have shown that rural water supply infrastructure is significantly easier to build than to maintain (Danert et al. 2010). Low population density, limited cash economies, and geographical isolation are just a few of the obstacles to water provision in rural areas. The perception of the diseconomies of scale condition in rural areas led to the promotion of community management as the preferred model of water supply management. Community management was defined by community participation throughout all development stages at the 1992 Dublin Statement on Water and Sustainable Development. Under this model, governments, multilateral institutions, and other implementing organizations within the WASH sector prioritize investment based upon community demand (often determined by proxy, such as user contributions) for a particular service level. Management is then transferred to the community after construction is complete and operation begins. After over a decade as the dominant paradigm in rural water management, research has determined that the community management model, particularly in Africa, was more widespread than the conditions for it to succeed (Harvey and Reed 2006).

As an example of the low sustainability in rural WASH infrastructure the IRC-International Water and Sanitation Centre of the Netherlands reported that over the past two decades nearly a third of the 600,000-–800,000 hand pumps installed in Sub-Saharan Africa have failed at a cost of US$1.2 to US$1.5 billion (IRC 2009). Another desk review of rural water supply experiences in 26 African countries reported between 24-30% (median) of systems are not functioning, with as many as 75% having failed in one country (Kleemeier 2010). The problems are not limited to Africa, a significant amount of research has uncovered the full scale of the problem worldwide (Gross et al. 2001; Lockwood 2002; Schouten and Moriarty 2003; Nolasco, 2010).

The questionable sustainability of rural water supply infrastructure has been an impetus for investigating alternatives to the community management model. Governments and other stakeholders have begun exploring alternatives to community management by enacting institutional and organizational transformations. These include a focus on marketization; i.e. the introduction of markets or market-simulating decision making techniques, and the participation of private companies and private capital in resource development of water supplies (Bakker 2003). Figure 1-1 presents the continuum of organizational structures for water supply provision from commercialized to non-commercialized. The upper left corner of the graph represents those arrangements where-in the public entity is the service provider. This is often manifested through a public municipal utility that operates as an autonomous or semi-autonomous institution from the regulatory function that the municipality would play as service authority[2]. This is a common service delivery model in the United States (Lockwood and Smits, 2012). The lower right corner represents arrangements where the government contracts private entities to provide WASH services. Under a concession contract a private entity may build and maintain infrastructure and provide services for long periods of time, decades in some cases. Under such long term contractual arrangements the service authority (institution responsible for guaranteeing service) transfers significant liability to the private entity with regard to service provision. Under these arrangements the service provided has the greatest autonomy and hence responsibility with regard to planning, financing, implementing, monitoring and supporting all aspects of service delivery. This arrangement is very common in developed countries and urban areas where economies of scale can be reached, but it has also been accomplished in rural areas in developing countries such as Benin, Colombia, and South Africa (Lockwood and Smits, 2012). Hybrid

[2] Service authority is the institution that fulfills the functions of planning, coordination, regulation, oversight, and technical assistance but not the actual service provision itself. Lockwood and Smits (2012) state that these authorities are typically located at the intermediate level in most countries although they work through local government (district, municipalities, or communes).

arrangements, called public-private partnerships have also been developed and achieved success in rural communities as demonstrated recently in Madagascar (Annis and Razafinjato, 2011).

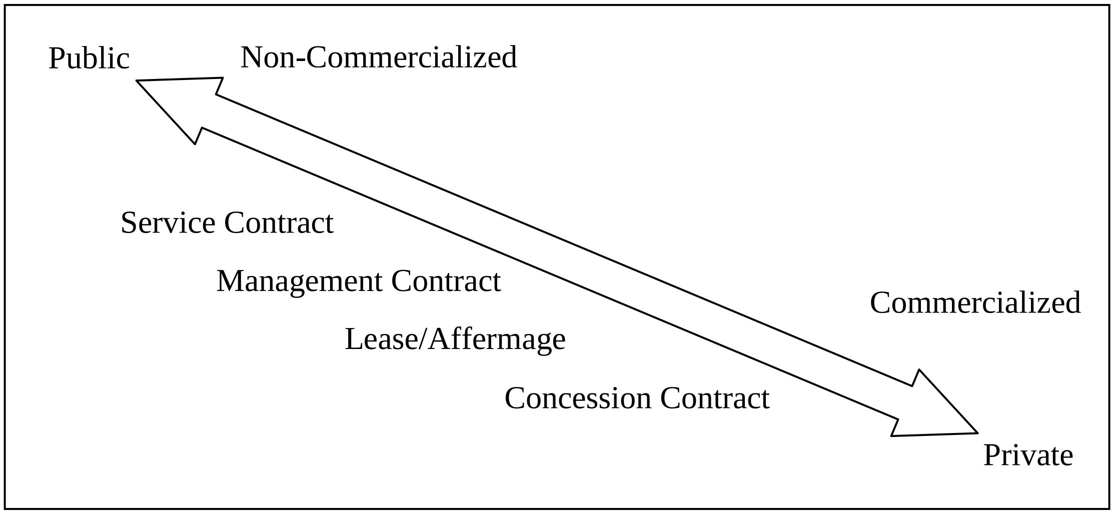


Figure 1-1 The continuum of organizational structures for water supply provision. Not listed on this graphic are arrangements such as "Build, Operate, and Transfer" contracts and cooperatives that can be located at various points on the continuum.

Another option referred to as self-supply is being explored involves a shift in emphasis away from communal ownership and management of water supply towards the individual household or family compound level. Self-supply is described as water supply user investment in water quantity and quality enhancements (e.g. boreholes, shallow wells with hand pumps, rainwater harvesting). It is based on incremental steps which are easily replicable and utilizes affordable technologies (Sutton 2009).

Alternatives to community management, such as self-supply and private management, have demonstrated the potential to succeed in certain instances where community management has failed (Kleemeier 2010; Sutton 2011). However, there are limitations to these alternative models as demonstrated by Oyo (2006). A few examples of these limitations include supply chain issues that limit the availability of spare parts in remote areas and the ability of private operates to achieve economies of scale and maintain profitability in low density areas (Oyo

2006) In addition, given the scale of the problem and the slow rate of change in development, it is imperative to investigate multiple models including revised versions of community management as well as other alternatives (Harvey and Reid 2006; Oyo 2006; Balkalian and Wakeman 2009). Understanding the strengths and weaknesses of the different management models is an important step in allowing development practitioners and governments to choose the appropriate model for a given context as no single model can been seen as a panacea for all situations (Lockwood 2002; Kleemeier 2010).

In order to facilitate a better understanding of the conditions for successful community management and improve the long term sustainability of services managed through this model; monitoring and evaluation tools must be developed and field surveys executed (Kleemeier 2010). Chapter 2 of this dissertation considers the indicators used to measure the sustainability of community managed systems, establishes a framework for evaluating systems in developing countries, and presents the results of an example analysis conducted in the Dominican Republic. An assessment tool is proposed that can be used to assess sustainability of rural water systems in developing countries.

In addition it is important for all those entities, whether communities, private operators or households, to understand the long term costs associated with the delivery of WASH services. These costs include both financial and economic costs. Chapter 3 of this dissertation presents the concept of life cycle costing applied to water services and identifies the household expenditures in these services. The methodology developed is applied to data collected in Burkina Faso as a part of the WASHCost project managed by IRC-International Water and Sanitation Centre.

1.2 Water Treatment

There has been significant research demonstrating the correlation between water quality and health (Esrey et al. 1991; Rose 2001; Trevett et al. 2005). Numerous studies determined that enhancing water quality was the more effective means at reducing relative risk of diarrhea compared to improvements in water quantity, sanitation, hygiene, or multiple interventions (Esrey et al. 1991; Waddington and Snilstveit 2009). However, Fewtrell et al. (2005) determined that water quality was less effective than water quantity at reducing diarrhea relative risk. Waddington and Snilstveit (2009) found water quality was less effective than water quantity, sanitation, hygiene, and multiple interventions at reducing relative risk of diarrhea. To ensure the continued health benefits of water from an improved source, effective management of supply infrastructure must occur throughout all life stages of a project, including operation and maintenance (McConville and Mihelcic 2007).

In the context of the questionable sustainability of water supply systems and service deterioration over time (e.g.-leaky pipes in distribution networks and negative pressures due to intermittent electrical supply) there is an increased risk that water quality from an improved source can be contaminated prior to reaching the point of use. Furthermore, effective infrastructure management is not a sufficient condition for ensuring water quality and eliminating health risks to consumers. Field studies have demonstrated that water quality from improved sources can deteriorate significantly after collection, while in transit to the household, and within the household prior to consumption (Gundry et al. 2006). As a result water treatment technologies implemented and managed at the household level and combined with safe storage practices are proposed as a means of reducing the risk of water contamination from the source to the household or within the household prior to consumption.

Household water treatment has also been suggested as an intervention to protect the approximately 780 million people worldwide without access to safe water (WHO/UNICEF 2010) and can also be an entry point for other water, sanitation, and hygiene promotion interventions. These points have been part of an ongoing debate regarding the acceptability and scalability of household water treatment (Clasen et al. 2009; Schmidt and Cairncross 2009a; 2009b). Schmidt and Cairncross believe that given the available evidence, potential effects of bias in field research conducted to date, as well as the lack of sufficient blinded controlled trials, it is premature to engage in widespread promotion of point of use (POU) water treatment. Schmidt and Cairncross argue that unlike POU treatment technologies, improving water access and sanitation is always worthwhile even if the true effect on health is small because of the time and cost savings associated with these interventions (Cairncross 1987; Black and Fawcett 2008; Schmidt and Cairncross, 2009a). Clasen and colleagues counter that over 850 million people who report using household water treatment technologies is evidence of their acceptability and scalability, and that the heterogeneity of health benefits reported in numerous trials, blinded and unblinded, is expected given the diversity of exposure (e.g. pathogens, transmission pathways, and preventative measures), interventions, methods of delivery, level of compliance, and study methodologies. However, both sides of this debate acknowledge the need for additional research, although they disagree to what extent POU treatment technologies should be promoted while this research is carried out (Clasen et al. 2009; Schmidt and Cairncross, 2009a; 2009b).

It is in the context of the debate over the appropriateness of household water treatment in the improvement of health, that a longitudinal study of one type of household water treatment, ceramic water filters, was implemented. Chapter 4 of the dissertation describes the results of a field assessment of two different commercially available ceramic water filters in the Dominican

Republic. This research seeks to contribute information for answering the question raised regarding the user acceptance and adverse effects of POU, specifically ceramic water filters. Chapter 5 of the dissertation addresses one major issue with regard to the user acceptance of ceramic water filters, i.e. flow rate, by developing and applying a mathematical model that describes the hydraulic flow regime of ceramic water filters which can be used to redesign ceramic filters to improve the flow rate.

1.3 Research Questions

There are several overarching scientific questions that will be addressed by the research. These include:

- What are the critical sustainability factors affecting management of rural water systems?
- What independent variables correlate with sustainable management of rural water supply infrastructure?
- What are the economic and financial household expenditures for accessing water in developing countries and what are the factors that affect these expenditures (e.g. socio-economic status, season, and service levels)?
- How do the service levels (water quantity, water quality, accessibility, reliability) relate to the household expenditures?
- What are the major barriers to water quality management at the household level?

A significant portion of this research is based on primary data collected in over sixty rural communities in the Dominican Republic and six rural and three peri-urban communities in Burkina Faso. Primary laboratory data for the ceramic water filter research (Chapter 4 and 5) was also collected at the University of South Florida and the Instituto Superior de Agricultura in

Santiago, Dominican Republic. The subsequent chapters will address the following specific topics:

- Chapter 2- Analysis of the Sustainability of Community Water Systems in the Developing World
- Chapter 3- Rural and Peri-Urban Water Supply Management: Understanding Household Expenditures
- Chapter 4- Assessment of the performance of clay ceramic water filters as a household water treatment technology
- Chapter 5- Mathematical Modeling of Ceramic Water Filters to Improve Hydraulic Performance

Chapter 2 will identify the most common factors affecting community management of rural water supply. A hybrid approach for measuring the performance of community managed schemes, based upon existing literature, is suggested. Finally, this hybrid approach is applied to a statistically representative sample of community managed systems through a case study in the Dominican Republic.

Chapter 3 seeks to analyze the long term costs to water service provision in rural and peri-urban areas by analyzing the life cycle costs. This chapter analyzes data that were collected in 9 sites in 3 regions of Burkina Faso between April and August of 2010 as a part of the WASHCost project under the management of IRC-International Water and Sanitation Centre based in the den Haag, Netherlands. The first objective of this research is to determine how household expenditure - financial, economic, and cumulative - in formal water sources varies across socio-economic status in the rural and peri-urban areas in Burkina Faso. The second objective is to characterize these expenditures and the water service levels (i.e. quantity, quality, distance, crowding and reliability) provided to the households and their socio-economic classification. The final objective is to uncover any seasonal differences in household expenditures or additional factors that may influence household expenditures on water services.

Chapter 4 explores an alternative to increased access/water quantity (which is directly and indirectly addressed in Chapters 2 and 3). This chapter addresses water quality managed at the household level through a household water treatment technology by assessing the specific performance of two different ceramic water filters (the paraboloid- and frustum-shape) in a rural community in the Dominican Republic. This research integrates field and laboratory performance with assessment of user preference.

Finally, Chapter 5 develops two mathematical models used to assess the hydraulic performance of ceramic water filters under typical usage. A mathematical model is developed for the two common filter geometries, which were researched in Chapter 4. Both models are calibrated with laboratory data and evaluated by comparison of model results to experimental data. The model is then used to assess how modification of filter design and usage may improve hydraulic performance and thus lead to increase in user acceptability.

2 WATER SUPPLY MANAGEMENT: ASSESSING SUSTAINABILITY OF COMMUNITY MANAGEMENT[3]

2.1 Research Objective

Consistent with recommendations to perform field evaluations of community management (Kleemeier 2010), this research seeks to: 1) develop an adaptable Sustainability Assessment Tool to evaluate community management of rural water supply systems around the world, and 2) test the tool by performing an assessment of a representative sample of communities with rural water systems in the Dominican Republic. This research serves as an *example* and *framework* for policy-makers and practitioners to ensure optimal sustainability of community management of rural water systems. In this research, sustainability is characterized by: equitable access amongst all members of a population to continual service at acceptable levels providing sufficient benefits, and reasonable and continual contributions and collaboration from service, consumers, and external participants.

2.2 The Rural Water Sector in the Dominican Republic

In rural areas of the Dominican Republic the population living within a fifteen minute round trip to an improved water source increased from 76% in 2000 to 84% in 2008. However, this increase was primarily due to urbanization which slowed the growth of the population living

[3] This chapter is adapted from an article "Assessing sustainability of community management of rural water systems in the developing world" that appeared in the *Journal of Water, Sanitation and Hygiene for Development*, volume 2, issue number 1, pages 20-30. It is included with permission from the copyright holders, IWA Publishing (see Appendix A for copyright clearance letter).

in rural areas. The absolute number of people with access to an improved source in rural areas increased by only 70,000 during this time (WHO/UNICEF 2010). The National Institute for Potable Water and Sanitation (INAPA) is the entity with default authority for provision of water and sanitation services. INAPA manages 71% of systems, para-statal corporations 10%, and community management organizations 19%, however, the latter is likely an underestimate since a large number of systems are undocumented (Rodriguez 2008).

2.3 Methods

In the Dominican Republic hand pumps, windmills, and rainwater catchment systems are not accompanied by the creation of a community management organization. Therefore in this study, all the communities selected had gravity fed/or motor assisted rural water supply systems. Utilizing INAPA and U.S. Peace Corps databases, 169 communities were identified with population $\leq$ 2,000 users and functioning systems (i.e. no permanent system damage or lack of service for > 1 year). Peace Corps represents "grassroots" level system design and community training because a volunteer lives and works with the community for two years.

2.3.1 Sample Size

From the cohort of 169 communities a geographically stratified and statistically significant random sample of 61 communities was selected following accepted methods (Sara and Katz 1997). Each selected community managed one water system. The total coverage across all 61 sample communities was approximately 35,000 users, which represents 1.3% of the total rural population with access to water (ONE 2010). See Figure 2-1 for a map of the communities.

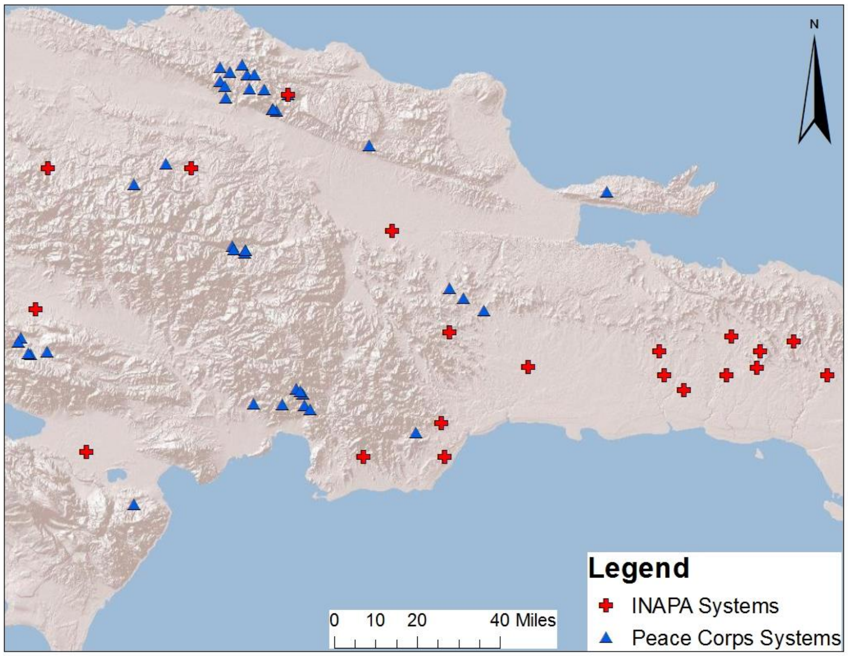


Figure 2-1 Map of sixty-one sample communities in the Dominican Republic. Twenty-one communities had INAPA designed systems and forty communities had Peace Corps designed systems

2.3.2 Data Collection

Primary data were collected using accepted methods (Sara and Katz 1997; Whittington et al. 2009) from community water committees, households (10% random sample per community), and key informants (e.g. community plumbers, institutional support personnel). Study protocol was approved by the Committee for the Protection of Human Subjects of Michigan Technological University, USA.

2.3.3 Selecting Indicators and Measures

The correct set of indicators and measures helps to calibrate progress toward sustainable development goals and provides an early warning to prevent economic, social, and environmental setbacks (UN 2007). Sustainability indicators can also simplify, clarify, and aggregate information for policy makers and practitioners.

Other sustainability assessment frameworks have detailed measures and targets for project rules and outcomes (Hodgkins 1994; Sara and Katz 1997; WSP-SA 1999) however they do not specifically focus on the factors affecting community management during the post construction phase. The Sustainability Assessment Tool developed in this research is novel because it focuses specifically on community management issues and is based on the findings of a systematic review focused on post-construction sustainability of community managed systems. That systematic review (Lockwood et al. 2003) identified twenty indicators after interviewing sector experts and reviewing 85 research publications from over 100 countries representing all eight of the UN Developing Regions. We condensed these 20 indicators down to 8 essential indicators by applying an assumption from Sugden (2003), that by measuring internal factors of a community, external factors are accounted for to obtain a "snapshot of sustainability." For example, if the community's technical skills are sufficient (or positively affect the sustainability of the system) and the pumps are working, then the training must have been sufficient to get to that point.

The resulting Sustainability Assessment Tool contains eight indicators (Activity Level, Participation, Governance, Tariff Payment, Accounting Transparency, Financial Durability, Repair Service, and System Function). Each indicator is represented by a specific measure(s) (two measures each for the Accounting Transparency and System Function indicators and six for the Financial Durability indicator) for a total of fifteen specific measures. The measures were chosen for ease of implementation and are drawn from the literature as proxies for their corresponding indicators. Targets were established for each indicator creating three sustainability categories (see Table 2-1). An overall sustainability score was also calculated using a weighting factor from Lockwood et al. (2003). The same sustainability categories (Table 2-1) were used for the overall sustainability score. This scoring methodology has been used in other conceptual frameworks (Sara and Katz 1997; WSP South Asia, 1999).

Table 2-1 Three sustainability categories. Communities are separated into one of three sustainability categories for each of the eight indicators. Using a weighting factor, the composite sustainability score was attained for each community. These scores, Sustainability Likely (SL), Sustainability Possible (SP), and Sustainability Unlikely (SU) correspond to the following qualitative descriptions.

Sustainability Likely (SL)	Organizational, administrative, and technical capacities are significant. Resources (financial and material) are available and sufficient for the most expensive maintenance process. Service levels and participation are reflective of a well-functioning system.
Sustainability Possible (SP)	Organizational, administrative, and technical capacities are acceptable. Resources (financial and material) are available but not sufficient for the most expensive maintenance process. Technical skills are acceptable for routine corrective maintenance.
Sustainability Unlikely (SU)	Organizational, administrative, and technical capacities are unacceptable. Resources (financial and material) are not available when needed or insufficient. Technical skills are unacceptable for maintenance demand.

2.3.4 Defining Targets

The targets (Table 2-2) for each of the eight indicators were developed from accepted values from literature in the rural water sector, INAPA and Peace Corps documentation, and the lead author's thirty-two month in-country experience. The following section includes a brief description of the targets for each indicator. See Schweitzer (2009) for more details.

2.3.4.1 Activity Level

In thirty percent, 18 of 61 communities, a pivotal moment in system management occurred when an active committee member moved out of the community or was not able to continue in their role, which had significant negative consequences on system performance. Having more "active" people (those who are capable of performing duties and cited in surveys and complying with their responsibilities) should mean that a community is more elastic and thus less susceptible to negative effects associated with the absence of any single "charismatic" individual. Yanore (1995) observed a similar impact of self-motivated individuals on system performance.

Accordingly, a rating of sustainability unlikely (SU) was assigned if there was zero or one active member on a water committee. Although, having more than two active members does not guarantee sustainability, having three or more reduces the probability of deadlock among active members. In other words, the probability of equal people voting opposite ways (i.e. "deadlock") on a binary decision (Yes/No) for two people is 50%, four is 38% and six is 28%. Therefore, sustainability possible (SP) was assigned if there were two active members and sustainability likely (SL) if it was identified there were three or more active members.

2.3.4.2 Participation

Previous studies demonstrate that increased participation of system users results in improved rural water project outcomes (Narayan 1994; Isham et al. 1995). In the Dominican Republic there are established targets: INAPA's "Reference Articles for Water Committees" which requires two-thirds majority approval of users to dissolve the committee or change by-laws. This establishes a critical participation target for effective governing of the system and suggests a likelihood of sustained project benefits (i.e. Sustainability Likely-SL). The second, INAPA's bylaws, establish the minimum attendance to establish quorum and proceed with meetings as 50% plus one. Although this target is not as explicitly related to sustainability, the author's experience corroborated by survey data and similar research shows that average percent attendance at community meetings below 50% is an indicator of problems (e.g. social cohesion). Low participation continued over long periods can compromise system performance (Prokopy 2002).

Table 2-2 The Sustainability Assessment Tool includes eight indicators. For each indicator the corresponding measures are listed. Targets for each indicator are listed defining three categories of sustainability unlikely (SU), sustainability possible (SP), and sustainability likely (SL).

Indicator	**Measures (reference)**	**Targets**		
		Sustainability Unlikely (SU)	**Sustainability Possible (SP)**	**Sustainability Likely (SL)**
Activity Level	1. Active water committee members (Yanore 1995)	1 person or less	2 people	3 people or more
Participation	2. Average percent attendance at community meetings (Narayan2002;Prokopy 2002)	Less than 50%	$50\% \leq X < 66.6\%$	66.6% or greater
Governance	3. Decision making process (Hodgkin 1994; INAPA 2008)	Minority decision No transparency	Majority decision Transparent but Arbitrary process	Democratic decision Community discussion Water committee facilitates
Tariff Payment	4. Percent debtors (Sara and Katz 1997; Fragano et al. 2001)	Greater than 80%	$80 \geq X > 10\%$	10% or less
Accounting Transparency	5. Accounting ledger 6. Report Frequency (Prokopy 2002; INAPA 2008)	Do not use ledger AND Report less than once a year	Use ledger OR Report at least once a year	Use ledger AND Report at least once a year
Financial Durability	7. Wages 8. Costs 9. Tariff 10. Average level payment 11. Connections, 12. Savings (Lockwood 2004; Dayal et al. 2000).	Income ≤ O&M AND Less than "significant savings"	Income > O& M OR "significant savings"	Income > O&M AND "significant savings"
Repair service	13. Downtime (Carter et al. 1999; Tynan and Kingdom 2002).	More than 5 days	1 to 5 days	Less than a day
System Function	14. Average Hours/Day 15. Average Days/Week (Fragano et al. 2001; Tynan and Kingdom 2002)	**Both** Less than 8 hrs.	**Pump System** $8 \leq X < 12$ **Gravity Systems** $8 \leq X < 16$	**Pump System** 12 hrs. or more **Gravity Systems** 16 hrs. or more

Note: "significant savings" is defined as the materials costs of replacing critical infrastructure as defined by Lockwood (2004). For a pump system the average cost in 2008 was $695 US and $278 US for gravity systems.

2.3.4.3 Governance

The only strictly qualitative measure used was for Governance. During the water committee and household surveys, individuals were asked to describe the committee decision making process. A comprehensive list of key words was utilized and accepted qualitative data analysis methods were used to stratify communities into three groups based upon whether the decision making process was 1) democratic, 2) systematic, and 3) transparent (Lofland and Lofland 2006).

2.3.4.4 Tariff Payment

The measure used is the percent of households owing three months or more of the monthly tariff. Although this does not explicitly represent willingness-to-pay, arguments have been presented that using more rigorous demand assessment techniques (e.g. contingent valuation methodology, revealed preference surveys) may be inappropriate for rural projects and programs (Parry-Jones 1999). Furthermore it was determined that in the sample communities, nonpayment did not simply reflect the ability to pay. The World Health Organization (WHO) recommends that user fees for basic water supply not exceed 3.5% of monthly household income (Walker et al. 2000). In no community did the tariff constitute more than 1.6% of the average monthly income reported for that province in the national census (CESDEM 2007) and in no community did the monthly tariff represent more than one half of an average day wage.

A frequency histogram of payment data was created and logical targets were identified using a technique similar to thresholding used in image analysis. Ten percent and eighty percent non-payment were used to establish the 3 sustainability categories for tariff payment. These reflect values observed in the field (Whittington et al. 2009) and in other assessment frameworks (Sara and Katz 1997; Fragano et al. 2001).

2.3.4.5 Accounting Transparency

INAPA recommends conducting at least annual financial reporting and having a basic accounting ledger (INAPA 2008). In all cases (n=61) when an accounting record was not used, the community was not collecting a tariff, and therefore the sustainability of the overall systems may be in question. Previous research established the connection between administrative tools (e.g. expenditure books, material registries) and the proper functioning of the systems (Prokopy 2002; RTI International 2006). Haysom (2006) showed that financial transparency vis-à-vis a formal savings account was correlated to successful system rehabilitation after breakdowns.

2.3.4.6 Financial Durability

The targets for financial durability are based upon the understanding that communities must cover operation and maintenance costs. It is recognized that true long-term financial sustainability requires cost recovery preparing for infrastructure replacement and expanding system capacity to accommodate growth (Whittington et al. 2009). Therefore in order to be sustainable communities must have sufficient income for recurrent costs and also have "significant savings" to cover eventual crisis maintenance activities (Lockwood 2004). In the Dominican Republic these types of expenditures include pump motors (for pump systems) and reconstruction/repair of river crossings or spring boxes after a catastrophic weather event (for gravity systems), but can be adapted to fit the local context. Systems will likely be sustainable (SL) if both conditions are met and possibly sustainable (SP) if one condition is met which is similar to other targets (Dayal et al. 2000). In communities with limited liquid capital and few assets, in the absence of sufficient tariff generation and without significant savings, system sustainability would be severely jeopardized (e.g. SU) by extreme weather events.

2.3.4.7 Repair Service

One way to indirectly gauge the functioning of the system is the efficiency of repair measured by system downtime, due to repair, per month (Carter et al. 1999). INAPA guidelines state the average operation and maintenance work requirements should be 6 hrs. /wk. (less than 51 connections), 12 hrs./wk. (51-150 connections), and 24 hrs./wk. (151-300 connections). These include preventative and corrective maintenance and therefore interruptions in service for over 24 hours would have to be considered crisis maintenance situations (following Lockwood, 2004) or reflect technical or administrative deficiencies in the repair service. No “crisis” situations (e.g. storm event) were reported for the month prior to the surveys and therefore SL is set as less than one day without service, which corresponds to internationally recognized targets (Carter et al. 1999; Tynan and Kingdom 2002). In order to account for extenuating circumstances, the SP-SU target was set at more than 5 days without service. This is consistent with the author’s experience and targets used by Sara and Katz (1997).

2.3.4.8 System Function

Hours per week with water in the system, obtained from community survey data, is the measure used to evaluate system function. To account for the effects of blackouts, gravity and pump system data were disaggregated. To control prohibited nighttime irrigation activities, communities shut water off at night for an average 8 hours (N=30 out of 44 gravity systems). Accounting for eight hours of suspended service, properly functioning gravity systems should operate sixteen hours a day (SL) which is consistent with research on water utilities in the developing world (Tynan and Kingdom 2002). Accounting for the apagon (blackout) effects on grid-dependent pumps and the lower service levels used in the design of solar panel pump systems (Karp and Daane 1999) target (SL) for pump systems was determined to be 12 hours. The difference between grid and solar pump systems was not statistically significant ($p<0.05$).

A commonly accepted minimum system function target, eight hours/day of water service (SU < 8 hrs./day), is cited elsewhere (Fragano et al. 2001). This value is also a peak demand benchmark commonly used in water storage design calculations (Rodriguez 2008). Therefore, the same minimum system function target (8 hours/day) was used for both gravity and pump systems. In the Dominican Republic it is believed that if system function is below this level, water is either being grossly misused, improperly partitioned, and/or the supply is inappropriate to meet demand. These targets should be readily adaptable to fit hand pumps and other technologies.

2.3.5 Other Indicators of Sustainability

The indicators presented here are those determined to be of highly critical importance with regard to the community management of rural water systems in the long term (Lockwood et al. 2003). There are additional institutional and policy factors as well as important environmental considerations (e.g. water source production, quality, conservation) that will likely have a strong bearing of the functioning of the system. However the Sustainability Assessment Tool presented here is meant to identify the indicators which impact community management, and not only the sustainability of physical infrastructure or the services provided.

There is research demonstrating the important connection between gender, domestic water management, and health (Makoni et al. 2004; Regmi and Fawcett 2001) as well as research highlighting the importance of gender and natural and water resource management (Lewis 2006; Rathberger 2006) However, Lockwood and colleagues (2003) concluded that gender was of less critical importance than the eight indicators listed above. For this reason gender was not included in Sustainability Assessment Tool, however an analysis of the relationship between gender and the findings of the pilot test of the tool in the Dominican Republic is included in the following section.

2.4 Results and Discussion

The objective of this research was not to compare INAPA and Peace Corps systems but rather to obtain a sample of communities with a representative range of systems and analyze their performance concurrently. Figure 2-2 provides a frequency histogram of the sustainability scores for the 61 communities included in the test of the Sustainability Assessment Tool. The data are binned into nine groups with Sustainability Unlikely represented by the first three bars (score 0-0.33), Sustainability Possible, the second three (0.33-0.67), and Sustainability Likely, the remaining (0.67-1.0).

Of the sixty-one communities included in the research sustainability is likely in fourteen (SL), possible in thirty-six (SP), and in eleven long term sustainability was determined unlikely (SU). In general, of the 61 communities, sustainability scores were poor (SU) in Participation (n=47) and Financial Durability (n=33) while communities were stronger (SL) in Repair Service (n=38) and System Function (n=35). This normal distribution is similar to an assessment of rural water supply project sustainability in six countries (Sara and Katz 1997).

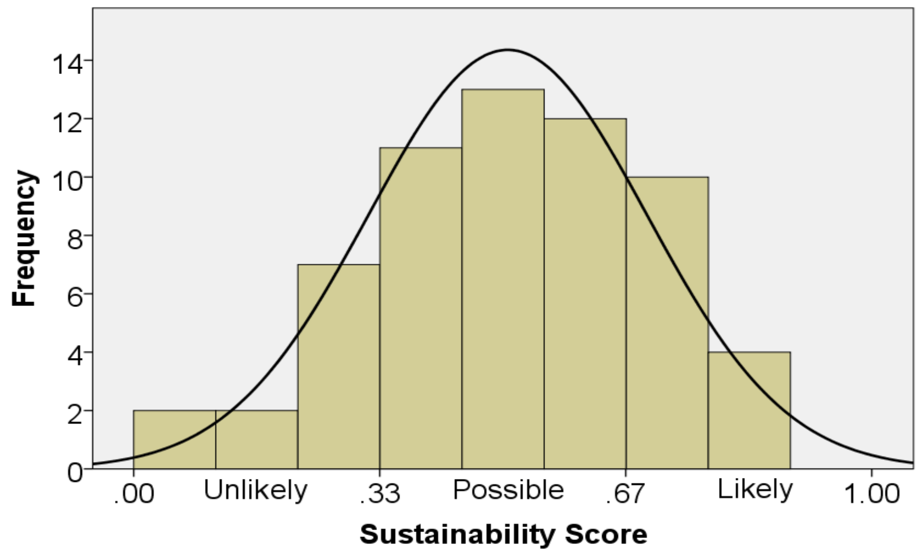


Figure 2-2 Frequency histogram of Sustainability Scores. A Sustainability Score from 0 to 0.33 corresponds to the Sustainability Unlikely (SU) category, 0.33 to 0.67 to Sustainability Possible (SP), and 0.67 to 1.0 is Sustainability Likely (SL). Histogram includes scores for 61 communities.

2.4.1 Correlating Sustainability to Other Independent Variables

A correlation analysis was performed to determine if the trends in the data from our study matched trends observed in previous research. Specifically if the scores from the Sustainability Assessment Tool could be correlated to other independent variables commonly included in monitoring activities and analyzed in previous research (e.g.-factorial analyses) on rural water supply project effectiveness (Sara and Katz 1997; Prokopy 2002; Whittington et al. 2009). For each community the composite sustainability score (Figure 2-2) and the scores for each indicator (available in Schweitzer 2009) were analyzed to determine correlation with other variables not included in the Sustainability Assessment Tool. These variables represent over 200 data points collected in each community from surveys and focus groups. The statistically significant results are presented below.

Table 2-3 Bivariate correlation analysis results. The Pearson's Product for parametric data and Spearman's Rho for non- parametric data is shown for a comparison between sustainability and indicator scores and different independent variables collected in 61 communities in the Dominican Republic. The values shown are the correlation coefficients.

Independent Variables (below)	Overall Sustainability Score	Sustainability Indicators							
		Activity Level	Participation	Governance	Tariff Payment	Accounting Transparency	Financial Durability	Repair Service	System Function
Attendance committee meetings (%)	.252*	.051	.041	.461†	.366†	.160	.121	-.280‡	.098
Capital contribution ($/household)	.303‡	.156	-.028	.124	.148	.253*	.371†	.056	.052
Size (# inhabited dwellings)	.295‡	-.063	.120	.218	.247*	.186	.359†	.003	.012
Community Water Storage (gallons)	.036	-.015	.346‡	.119	-.071	-.080	.188	-.236	-.264*
In kind labor contribution (# days/household average)	-.099	-.472‡	.279	-.321	.041	.023	.109	-.113	.099
Election frequency (months)	-.392*	.171	-.551‡	-.384†	-.188	.031	-.217	-.229	.159
Maintenance (hrs./month)	.340†	.240*	-.071	.193	.376†	.351†	.143	-.137	.341†
Plumber wage ($/month)	.384†	.182	-.148	.384†	.467†	.243*	.103	-.040	.308‡
Support visits (#visits/yr.)	.206	.252	.353†	.052	-.041	.147	.363†	.085	-.259‡
Distance to seat of municipality (km)	-.055	.123	.048	-.033	-.197	-.015	.047	-.207	-.070
Shared taps (% total)	-.316‡	-.394†	-.081	-.009	-.129	-.235*	-.257‡	.019	-.030
System Age (yrs.)	-.381†	-.367†	-.201	-.042	-.227*	-.277†	-.382†	.067	.081
Last committee meeting (months)	.154	.004	.329‡	-.199	.040	-.352†	.309‡	-.018	.063
Total elections held since creation (#)	-.137	-.265‡	-.208	.336†	.038	.005	-.189	-.073	-.021
Solicited outside Help (# times/yr.)	-.085	.128	.114	.213	-.092	.053	-.080	.033	-.323‡
Previously recorded non-payment of tariff (%household)^	-.546	-.258	-.364*	.004	-.482‡	-.610†	-.476‡	-.253	.020
Connection fee ($)	.355*	.051	-.238	.472‡	.425‡	.316	.258	-.191	-.006
Number of women on water committee	-.084	.169	.032	-.007	-.163	-.200	.018	-.126	-.081
Women on water committee (% of total members)	-.028	.230*	-.580	-.092	-.043	-.011	-.192	-.120	-.088
Number of active water committee members that were women (% of total active)	.261‡	.348†	-.001	.009	.250*	.345†	.115	-.083	.296‡
Average education level of water committee members (grades completed in school)	-.104	.312‡	.213	-.007	.001	.138	-.014	-.313‡	.044

Note: A negative correlation coefficient means that the assessment score and independent variable are inversely related. As values for one increase, values for the other decrease and vice versa.
† Significant at 0.01 level (p<0.01). ‡ Significant at 0.05 level (p<0.05). *Significant at 0.10 level (p<0.10).

From the results of the correlation analysis (Table 2-3), the independent variables most closely correlated (0.01 significance) to the overall composite sustainability score were system age (negative correlation), plumber wage, and hours spent on maintenance activities per month. Systems age was also negatively correlated ($p<0.01$) to activity level, accounting transparency, and financial durability. One possible explanation for the age related trends is that the motivation of active individuals and organizational capital of the community decrease with time. Anecdotal evidence from sample communities in our research suggests that one reason for the decrease in activity may be that individuals lose interest in providing their services with little or no remuneration. This may be especially true if individuals feel alone in their duties and abandoned by outside organizations (e.g. civil society organizations, local government, INAPA, etc.), although no statistically significant ($p<0.1$) correlation between activity level and outside support visits was observed for the sample communities.

Community participation and financial durability were found to increase with more visits by supporting organizations ($p<0.01$), a finding supported by others (Lockwood et al. 2003; Kayser et al. 2009). Improved financial durability was correlated to upfront capital contribution to water system costs as well as community size ($p<0.01$). Increased transparency was correlated to higher payment of the monthly tariff ($p<0.01$), supported by Prokopy (2002). Higher tariff payment also corresponded ($p<0.01$) to increased time dedicated to maintenance activities and the money spent on wages (plumbers and tariff collectors). Similar to Haysom (2006) no correlation was found between system age and function or repair service, so it is unclear why transparency and tariff payment were better in younger systems. One possibility is the increased social capital at project completion which decreases with time, although this was not measured in this study. Performing more maintenance activities ($p<0.01$) and having greater savings (p=0.013) correlated to better system function, specifically more hours of water service per day. Such systems were less likely to solicit help from an outside organization (p=0.01) and more likely to pay their plumbers a higher wage (p=0.02).

The percent of shared taps, initial contribution to capital costs averaged over all households, and the total size of the community were also significant (p<0.05) to sustainability scores. Activity level increased (p<0.01) as the percent of public taps decreased suggesting that improved service levels (e.g.- private verses public taps) may motivate more individuals to take an active role in system management, which has the added benefits previously mentioned. This is important for policy makers as it could indicate that short term savings related to lower service levels may actually require increased inputs over time. Lastly, the decision making processes improved with increased attendance at water committee meetings (p<0.001) and frequency of these meetings (p=0.007) and more frequent elections (p=0.003).

2.4.2 Gender and Sustainability

The difference in average overall sustainability scores for communities with women on the water committee compared to communities with all male committees was statistically significant at 94% level (p=0.053). All male committees had average scores of 40% (n=11) while those with at least one woman averaged 53% (n=50). This confirms previous findings that gender participation in water committees is important (Regmi and Fawcett 2001). Although there was no correlation between the number of women on the water committee and the overall sustainability score (see Table 2-3), there was a correlation between the number of active individuals that were women as a percent of total number of active and overall sustainability. As the number of active women increased there were improvements in activity level, accounting transparency, system function, and overall sustainability as measured here. In other words, having people (men or women) that are active is more important than having more women on the committee; however, amongst active people, having women who are active has a greater effect than having men who are active. Therefore although Lockwood and colleagues (2003) determined from their review of 85 different publications on sustainability that the involvement of women is of "less critical importance" compared to other indicators, it is important to understand the type of involvement and to encourage women to take an active role on the water committee.

This research suggests that ensuring that women play and active and instrumental role in the management of water resources is a critical factor in the long-term sustainability of water supply systems. Therefore, an additional indicator could be added to the sustainability assessment tool to address the importance of gender. In the Dominican Republic, the government recommends at least 40% of the water committee be composed of women. Ideally, women would have equal representation on the water committee. Of the water committees interviewed in this research, women composed 32% of all of the water committee members. The average committee had 2 members that were women and most often these women were secretaries or treasurers.

Although only 26% of the women were considered to be active members (compared to 39% of men), the average education level of the women was 8.2 years of schooling verses 6.0 for men. This suggests that there is a significant opportunity to more effectively engage women in the water committee. Table 2-4 presents an example of a gender indicator that could be added to the Sustainability Analysis Tool and the respective targets defining the levels of sustainability that would be appropriate in the Dominican Republic.

Table 2-4 Sustainability Analysis Tool gender indicator. The targets presented are based upon the standards and norms in the Dominican Republic; however they could be modified to fit the local country context where the tool is applied.

Indicator	Measures (reference)	Targets		
		Sustainability Unlikely (SU)	Sustainability Possible (SP)	Sustainability Likely (SL)
Gender	Number of women on the water committee (INAPA, 2008)	None	Less than 40%	More than 40%

2.5 Conclusions

A Sustainability Assessment Tool composed of eight essential indicators with easily defined measures and specific targets was developed and then used to evaluate the sustainability of community management of water supply systems in 61 rural communities in the Dominican Republic. In this study, 72 percent of systems were assessed to be likely or possibly sustainable, with the remaining 18 percent assessed as unlikely to be sustainable. Communities that were visited more often by supporting agencies experienced better community participation and financial durability. Systems that had more transparent accounting had higher compliance with the monthly tariff payments. However as a water system aged, this transparency decreased which may be a result of the number of active individuals participating with the water committee in the community. System age was also strongly correlated to the scores for the sustainability indicators.

The findings demonstrate the importance of long term involvement by outside groups to support community management activities. This has significant implications when developing budgets because long-term costs may be higher than previously assumed (Gibson 2010). Many organizations working in the WASH sector have recognized the importance of continued support to communities in addition to the value of long term monitoring and evaluation. International NGOs have made commitments to build the support capacity of local governments and bilateral donors have included clauses in contracts with implementing organizations requiring them to monitor the sustainability of infrastructure over time (i.e. sustainability clauses). The framework presented in this chapter serves as a diagnostic tool to inform decision making, characterize specific needs of rural communities in the management of their water systems, and identify weaknesses in training regimes or support mechanisms. It can also be adapted by modifying specific targets to fit locally appropriate conditions. It is crucial that any sustainability assessment tool be appropriately contextualized to meet the conditions and context of the country or region in which it will be applied. For example, after analyzing the effects of gender on sustainability scores it was clear that a gender indicator should be included in subsequent sustainability monitoring activities in the Dominican Republic. Ultimately, use of this framework should result in health improvements by ensuring equitable access to continual service at acceptable levels.

3 WATER SUPPLY MANAGEMENT: UNDERSTANDING HOUSEHOLD EXPENDITURES[4]

3.1 Introduction

Research has demonstrated the inequality in access to improved water sources between rich and poor households. For example, the most recent Joint Monitoring Program (JMP) report showed 97 per cent access to improved water sources for the richest quintile in urban areas worldwide, while only 10 per cent of the poorest quintile in rural areas had similar access (UN 2012). In addition there is a recurrent theme in water provision across the developing world-that the price of water is inversely related to the ability to pay (UNDP 2006). For example, in Jakarta, Lima, Manila and Nairobi, households living in low-income and informal settlements typically pay five to ten times or more for their water than high-income residents in the same city (UNDP 2006). In addition, another study showed that the poorest 20 per cent of households in Argentina, El Salvador, Jamaica and Nicaragua allocate more than 10 per cent of their overall spending to water (Dhanuraj et al. 2006).

Although there is evidence that poorer households pay more for their water than wealthier households, most of the present research is limited to financial expenditure and based on self reported aggregate expenditures on water-mainly from private water vendors (Keener et al. 2010). In addition, it is very important to consider the economic expenditures (i.e. time and

[4] This chapter is adapted from a report published by the IRC-International Water and Sanitation Centre entitled "Household Expenditure on Water Service-Financial and economic expenditures across socio-economic classes and seasons in Burkina Faso" (Schweitzer et al. 2013).

other non-pecuniary inputs) in addition to the financial expenditures when considering the total cost to households for water services.

Economic expenditure is particularly relevant in the context of gender roles and the household division of labor. It is well established that water collection is more commonly carried out by women and girls (Hutton and Haller 2004). For adult women, water collection reduces the time available for other activities including child care, productive work or rest which reinforces time-poverty, disempowers women and lowers income. Water collection contributes to gender gaps in school attendance and lower school attendance for girls has significant and far-reaching consequences. Educated girls are more likely to have smaller, healthier families as adults and their children are less likely to die and more likely to receive an education than children of less educated mothers (Pushpangadan 2000).

Analysis of household economic expenditure in water service has primarily taken place through demand estimation studies. In addition, almost all the household economic studies from developing countries are conducted in medium to large-sized cities and tend to be focused on piped household connections (Nauges and Whittington 2009). Few studies focus on non-tap sources (Nauges and Strand 2007) or communities with less than 10,000 inhabitants (Mu et al. 1990). Few studies also provide empirical evidence about the non-pecuniary costs of collecting water from non-tap sources (Mu et al. 1990). Due to an abscence of demand information, rural and peri-urban areas should be a high priority research area (Nauges and Whittington 2009).

This research analyzes total household expenditures (financial and economic) on water services and seeks to add to the lack of information on this topic. Determining the total expenditures (both financial and economic) made by households is not only novel, but most importantly, useful to understanding the decisions that households make/are forced to make regarding water service. This information is also necessary for those designing local policies that address poverty, health, and equity.

3.2 Research Objectives

The first objective of this research is to determine how household expenditure - financial, economic, and cummulative - in formal water sources vary across socio-economic status in the rural and peri-urban areas in Burkina Faso. The second objective is to characterize these expenditures and the water service levels (i.e. quantity, quality, distance, crowding and reliability) provided to the households and their socio-economic classification. The final objective is to uncover any seasonal differences in household expenditures or additional factors that may influence household expenditures on water services.

This research is conducted to compliment the overall objectives of the WASHCost project[5]. WASHCost is an action research project investigating the costs of providing water, sanitation and hygiene (WASH) services to rural and peri-urban communities in Burkina Faso, Ghana, Mozambique and India. The stated goal of WASHCost is to provide policy makers and planners with tools and strategies for effective planning, budgeting and spending in the WASH sector to lead to more sustainable, affordable and appropriate services (Moriarty et al. 2010a). To meet this goal, WASHCost has been collecting and disaggregating life-cycle cost data for WASH services in order to understand the drivers of cost and therefore enable more equitable and cost effective service delivery. This particular research focuses on data collected in Burkina Faso.

[5] For more information on WASHCost visit http://www.washcost.info/

3.3 Methods

The United Nations Development Program ranked Burkina Faso 177th out of 182 countries in terms of Human Development. It has a gross domestic product (GDP) per capita of 219,843 F CFA in 2010 (IMF 2011) which places it as one of the poorest countries in the world. Data were collected in 9 sites in 3 regions of Burkina Faso between April and August of 2010 as a part of the WASHCost project. Table 3-1 provides an overview of the 9 sites of data collection. The table shows that 3 peri-urban and 6 rural sites were included and the population of the sites ranged from 1,519 to 15,014.

Table 3-1 Overview of the Burkina Faso data collection sites (Source: WASHCost Census).

Region	Site	Density	Population
North	Ouahigouya, Sector 1	Peri-Urban	7,418
	Aorema	Rural	4,096
	Margo	Rural	2,101
Hauts-Bassins	Hounde, Sector 2	Peri-Urban	1,568
	Bouere	Rural	7,299
	Dossi	Rural	3,688
Center	Ougadougou, Sector 30	Peri-Urban	15,014
	Yagma	Rural	1,519
	Komsilga	Rural	1,704

A general census was conducted between April and June 2010. Table 3-2 provides an overview of the information that was collected in addition to demographic information about the household and concession (i.e. family compound). Detailed surveys were conducted in random households to determine information on user preferences and behaviors related to water, sanitation and hygiene. A second sample of households was selected and surveyed in August 2010 to capture the variation in WASH practices between the dry and wet seasons. In addition to the household surveys, data were collected at 88 out of 136 water points in 9 communities over 37 days between April and August of 2010.

Table 3-2 Overview of WASHCost data collection tools. Results used for nine Burkina Faso sites.

Census	Household Surveys	Water Point Surveys
7,399 households GIS data of concession Household size Water source (1st and 2nd preferred) Daily water usage Sanitation type Qualitative soicioeconomic status Dry season only (April-June)	492 households (dry) 518 households (wet) 363 households (both) GIS data of concession Household info Water Point info Daily water usage Collection containers Satisfaction Water Storage/Transport Sanitation/Hygiene information Assets/Income/Expenses	7,854 individuals surveyed GIS data of 86 water points Household info Name/age of water collector Container type/quantity Number of trips Total quantity of water Time at water point Transportation mode Improved water points only Dry season April- June (n=6,928) Wet season August (n=954)

3.3.1 Cost Categories

The life-cycle cost categories used in this research are based on the categories developed by the WASHCost project (described in Table 3-3). For information on these categories see Fonseca et al. 2011, and for more information on life-cycle costing water systems and water services in Burkina Faso see Pezon et al. 2012 and 2013.

Table 3-3 Components of WASHCost life-cycle cost.

Cost Components		Brief Description
Capital Expenditure (CAPEX)	Capital Expenditure Hardware(CapExHrd)	Capital investment in fixed assets, such as concrete structures, pumps, pipes and latrines either to develop or to extend a service.
	Capital Expenditure Software (CapExSft)	Expenditure on one-off work with stakeholders prior to construction or implementation, extension, enhancement and augmentation
Recurrent expenditure	Operational Expenditure (OpEx)	Recurrent (regular, on-going) expenditure on labor, fuel, chemicals, materials and purchases, etc.
	Capital Maintenance Expenditure (CapManEx)	Asset renewal and replacement cost; occasional and lumpy costs that seek to restore the functionality of a system
	Cost of Capital (CoC)	Cost of interest payments on micro-finance and any other loans.
	Expenditure on Direct Support (ExpDS)	Expenditure on support activities for service providers, users or user groups.
	Expenditure on Indirect Support (ExpIDS)	Expenditure on macro-level support, including planning and policy making, and support to decentralized service authorities.

3.3.2 Water Service Levels

Moriarty et al. (2010b) developed the concept of water service levels in order to provide a framework for aggregating and benchmarking critical indicators of water service for use in planning and analysis. Defining service levels is a necessary condition for comparing costs; for example in comparing the costs between management models or across geographic regions. The indicators that are used in WASHCost to define service levels include: 1) the quantity of water available to households, 2) the relative quality of that water[6], 3) the accessibility of the water source(s), and 4) the reliability of service (i.e. functionality). The service level categories used in WASHCost include: 1) high, 2) intermediate, 3) basic, 4) sub-standard, and 5) no service.

The benchmarks used to determine these categories were derived from national norms and standards in each country. A more complete discussion of how these service levels and benchmarks were determined for Burkina Faso is provided by Pezon et al. (2012). The benchmarks and corresponding service level categories are provided in Table 3-4. To determine the service level for each individual household, data were obtained from the household surveys (e.g. distance to water points, volume of water consumed daily), water point surveys (e.g. number of people observed using individual water points), and government records (e.g. water quality testing, design capacity of water provision technologies). Although WASHCost service level categorization includes reliability of services as an indicator, the government of Burkina Faso does not systematically collect this information. Therefore, reliability is excluded from the overall service level determination and the subsequent analyses presented in this report.

[6] In Burkina Faso the water quality data collected did not include sufficient detail to accurately compare water quality across all technologies and communities, therefore the frequency of water quality monitoring activities was used as the service level indicator.

Table 3-4 The four WASHCost Burkina Faso service level indicators. Corresponding source of data is shown for each indicator: Water Quantity, Water Quality Monitoring, and Accessibility. The first column lists the Service level categories and subsequent columns have the thresholds or benchmarks which define each category.

Service Level Categories	Quantity (liters/capita-day)	Water Quality Monitoring	Accessibility	
			Distance from Household	Crowding
Data Source	Household Surveys	Burkina Government	GIS information	Burkina Government and Water Point Surveys
High	**Rural** $X \geq 60$ lpcd **Peri-Urban** $X \geq 100$ lpcd	**Formal Sources** Annual testing	**Household Connection**	$POP_{OBSERVED} \leq POP_{DESIGN}$
Intermediate	**Rural** $60 > X \geq 40$ lpcd **Peri-Urban** $100 > X \geq 80$ lpcd	**Formal Sources** Tested once at installation or rehabilitation	**Handpumps** $X \leq 1{,}000$ meters **Standpipe** $X \leq 500$ meters	
Basic	**Rural** $40 > X \geq 20$ lpcd **Peri-Urban** $80 > X \geq 40$ lpcd			
Sub-standard	**Rural** $20 > X \geq 5$ lpcd **Peri-Urban** $40 > X \geq 10$ lpcd			$POP_{OBSERVED} > POP_{DESIGN}$
No Service	**Rural** $5 > X$ lpcd **Peri-Urban** $10 > X$ lpcd	**Formal Sources** No testing **All informal sources**	**Handpumps** $X > 1000$ meters **Standpipe** $X > 500$ meters	

Key: GIS-Geographic Information System; lpcd- liters per capita per day; POP-Population

3.3.3 Socio-economic Status

Socio-economic status or poverty can be measured in absolute and relative terms. The former affords the advantage of comparisons between different geographic locations and time periods. Therefore, for monitoring and evaluation purposes governments and development agencies have created various frameworks and thresholds for defining poverty in absolute terms.

Poverty can also be defined in relative terms, which proponents argue provides more context specific and therefore perhaps more relevant results. However, the flexibility for comparison between countries or regions may be limited with relative poverty measures.

Principal component analysis (PCA) is a mathematical procedure which converts a large range of variables in a condense group of principal components that most closely represents the variability in the original group. PCA was performed on the household asset data in order to determine the minimum number of variables that will account for maximum variance in the data. The main advantage of principal component analysis over income and consumption based methods is that measurement problems involving recall bias, seasonality, and data collection time are minimized (Jobson 1992; Mckenzie 2003). The data were evaluated using principal component analysis as well as existing classification systems. However, after careful consideration it was determined these methods were not preferable as they failed to meet one or more of the criterion (e.g. sample size, factorability of correlation matrix, and/or linearity) commonly suggested for their application (Tabachnick and Fidell 2007). Therefore two methods were utilized in this analysis to categorize households by socio-economic status.

The first methd used to determine SES utilized a comparison of household expenditure (SES-1[7]) against National Poverty Level, resulting in to categories:Non-Poor or Poor. SES-1 is a quantitative classification that incorporates a national poverty benchmark of 108,454 CFA/person/year[8], established by the National Institute of Statistics and Demography (INSD) of Burkina Faso. This value is based on data obtained from the Preliminary Survey on Household Living Conditions 2009 (EICVM-Enquête intégrale sur les conditions de vie et des ménages) and Demographic and Health Survey. WASHCost surveys collected information on household

[7] For a complete list of the variables used in this chapter see Appendix C
[8] Equivalent to 215.93 USD/person/year (exchange rate used: 1 USD=502.271 CFA (September 2012)

income and expenditures. Research has demonstrated that expenditures may be a more accurate measure of welfare than income (Meyer and Sullivan 2006). Therefore self-reported "usual" monthly expenses were used, as consumption measures based on recall periods of less time are not suitable for the construction of welfare classifaction categories (Zaidi and Deaton 2002). These monthly expenses were aggregated over a year and compared to the national poverty level previously mentioned to categorize households as poor or non-poor.

The second method used participatory assessment to determine socio-economic status (SES-2) resulting in three categories: Non-Poor (NP), Poor (P), Very Poor (VP). Participatory assessments measure poverty in terms of local perceptions of poverty, which are identified and then extrapolated and quantified in order to construct a regional poverty categorization system. Proponents argue that such a poverty categorization system is more comprehensive and represents the multidimensional nature of poverty and the processes that create and maintain it. With this indicator, poverty is defined locally in terms of perceptions of well-being and how neighboring informants rank this perception. Utilization of this measure is thus limited to areas where people know about their neighbours, usually rural communities or within neighborhoods in urban or peri-urban settings. The number and location of communities in a chosen area are selected using a maximum-variation sampling strategy, taking into account factors that may explain expected variation in perceptions of well-being in the area of study.

WASHCost Burkina Faso conducted focus group sessions in each of the nine communities where data collection took place to determine socio-economic status (SES-2). Criteria for the inclusion in one of three groups used in SES-2: Very Poor (VP), Poor (P), or Non-Poor (NP), were identified by focus group participants. Households were subsequently assigned socio-economic status (SES-2) based on these criteria by people within the community.

These criteria included access to adequate food, clothing, housing, and agricultural lands. Appendix D provides additional information on the criteria used to classify households. The quantitative classification (SES-1) was used to verify the qualitative classification system (SES-2). In no cases were households listed as VP for the qualitative system (SES-2) listed as NP for the quantitative system (SES-1). Similarly in no cases were households listed as NP for the qualitative system (SES-2) listed as P for the quantitative system (SES-1).

3.3.4 Expenditures

Detailed expenditure data were collected for approximately 500 households. The data available for household financial expenditure is shown below and separated by one time investments and recurrent expenditures. Three of the seven WASHCost life-cycle cost components (see Table 3-3) are represented: CAPEX, OPEX, and CAPMANEX. Each are discussed below.

3.3.4.1 Financial Expenditures

The data for the financial expenditures calculations were derived from the household surveys. The capital, or ”one-off” expenditures are determined using equation (3.1). No differentiation was made between hardware and software expenditures.

$$\text{CAPEX} = \frac{\text{INV8}}{HH\ size} \tag{3.1}$$

where:

CAPEX = One off expenditures ($ per person)

INV-8 = Value of investement in implementation of infrastructure (all sources)

HH size = Number of members of the household

There are two types of recurrent expenditures made by households: OPEX and CAPMANEX. From the household survey data it is possible to calculate the financial OPEX via two different methods as shown in equations (3.2) and (3.3). OPEX2 is based upon a recall of daily activies (i.e. the number of receptacles used to collect water each day and the cost of filling each receptacle), while OPEX1 requires that the respondent estimates the average expenditure on water for the previous year. Research has suggested that long term recall of expenditures may introduce significant bias (Kasprzyk 2005). Therefore OPEX2 is assumed to be more accurate estimate of operation expenditure and is used in subsequent calculations of total financial expenditures (Financial_EX). It is referred to as $OPEX_{FIN}$ for the remainder of the dissertation.

$$\text{OPEX1} = \frac{\text{INV13}}{HH\ size} \tag{3.2}$$

$$\text{OPEX2 or } OPEX_{FIN} = \frac{\text{INV4 x 365 days}}{HH\ size} \tag{3.3}$$

where:

OPEX = Recurrent cost of water ($ per person per year)

INV-13 = Estimated yearly expenditure on water (all sources)

INV-4 = Daily amount paid for filling all receptacles (all sources); and

HH size = Number of members of the household

CAPMANEX or capital maintenance expenditures are the occasional expenditures, in the form of money, labor and materials for asset renewal or replacement that seek to restore the functionality of a system. CAPMANEX is determined using equation (3.4).

$$CAPMANEX = \sum_{N=1}^{i} \frac{INV10 + \text{INV11} + \text{INV12}}{AGE\ x\ HH\ size} \tag{3.4}$$

where:

CAPMANEX = Asset renewal and replacement ($ per person per year)

INV-10 = Value of investement in repair i^{TH} sounce

INV-11 = Current cost of containers used to transport water

INV-12 = Current cost of storage containers

AGE = Age of i^{TH} water soure; and

HH size = Number of members of the household

The financial expenditure on water for each household (Financial_EX) is the total recurrent financial expenditure calculated by adding CAPMANEX and $OPEX_{FIN}$. This is determined as follows.

$$\text{Financial\_EX} = \quad \text{CAPMANEX} + \text{OPEX}_{FIN} \tag{3.5}$$

3.3.4.2 Economic Expenditures

In determining the economic expenditure in water collection, previous studies have considered: 1) round trip walking time to the source (Strand and Walker, 2005), 2) walking and waiting time at the source (Larson et al. 2006), and 3) linear distance from the household to the source (David and Innocencio 1998). However, all of these studies occurred in urban areas, using self-reported data, and did not quantify the financial costs of collecting water (Mu et al. 1990). To estimate the costs of water collection, data obtained from the household and water point surveys were used. These data include: 1) type and number of containers used to collect water, 2) total quantity of water collected, 3) number of trips to carry water back to the household after filling, 5) the time spent queueing at the water point, and 6) the type of transportation used to arrive at the water point.

The total economic expenditure is the sum of time dedicated to the collection, transport, and storage of water multiplied by the financial value of this time. This is also know as the opportunity cost of water ($OPEX_{ECON}$) and is described by equation (3.6).

$$OPEX_{ECON} = \frac{v}{\text{HH size}} * \sum_{N=1}^{i} \left\{ \frac{(2d_N * r_N)}{s} + t_N \right\} \qquad (3.6)$$

where:

$OPEX_{ECON}$ = total opportunity cost for handling of water (e.g.-collection, transport, storage) ($ per person per year)

HH size = Number of members of the household

i = Total number of water sources

d_N = One-way distance (in meters) traveled from household to source N

t_N = Average queue time at source N

s = Speed of travel (assumed to be 55 meters per minute)

r_N = Number of trip back to the househould per fill up at the water point N; and

v = value of household's time (derived from household surveys)

One difficulty in determining the opportunity costs of the time dedicated to water collection is the time valuation of the water collector. Variables such as age, sex, education level, local labor markets and unemployment levels can factor into the earning potential calculations. The case has been made for using the GDP per capita-value added in manufacturing based upon the idea of loss of productivity for adults and the long-term earning potential of children (Hutton and Haller, 2004). Others suggest using minimum wage rate for unskilled labor (Whittington et al. 1990), which in Burkina Faso is 162.37 CFA (US$ 0.32) per hour. The Inter American Development Bank uses a more conservative value, 50 per cent of the market wage rate for unskilled labor (i.e. 81 CFA per hour), as the valuation of time based upon transportation research in the developing world. For this study the value of the households' time (*v)* is based upon the annual household revenue (Rev_TOT) reported in the detailed household surveys (See equation B.2 in Appendix E). Appendix E provides a detailed description of the value of household time (*v)* and the other assumptions used in determining the input values for equation (3.6).

3.3.4.3 Absolute and Relative Expenditures

For the households that were surveyed in both the wet and dry season (n=363) a cummulative expenditure on water was calculated using the financial and economic expenditures, see equation (3.7). An eight month dry season (October through May) and four month wet season (June through September) were used to determine the annual expenditures.

$$\text{Cumulative\_EX} = \text{CAPMANEX} + \frac{8}{12}\left(\text{OPEXfin}_{DRY} + \text{OPEXecon}_{DRY}\right) + \frac{4}{12}\left(\text{OPEXfin}_{WET} + \text{OPEXecon}_{WET}\right) \quad (3.7)$$

In order to understand the true financial and economic burden of household expenditures on water it is necessary to consider, not only ABSOLUTE expenditures, but also expenditures on water RELATIVE to total household income[9]. Therefore the total financial expenditure on water (Financial_TOT) was normalized by the annual reported household income (Rev_TOT). Declarations of individual or household income are often seen as underestimates of actual values and therefore total household expenditures on all goods and services is commonly used to reflect

[9] In order to control for household size effects the data was analyzed both on a cost 1) per person per year, which is denoted by variables with an "EX" suffix and 2) per household per year, which is denoted by "_TOT" suffix. For example the units of Financial_EX are US$/person/year while Financial_TOT are US$/household/year.

welfare (Somda et al. 1999). Accordingly the financial expenditures were also normalized by the cumulative household spending (Exp_TOT). The calculations to determine these financial expenditures are shown in equations (3.8) and (3.9). Note this normalization can also be performed for the cumulative expenditures as well.

$$\text{Financial\_prct\_exp} = \frac{Financial\_TOT}{Exp\_TOT} \tag{3.8}$$

$$\text{Financial\_prct\_rev} = \frac{Financial\_TOT}{Rev\_TOT} \tag{3.9}$$

3.4 Analysis of Household Expenditure

3.4.1 Overview

In each of the nine communities a comprehensive census and water point survey was conducted. In addition, subsets of households were randomly selected to participate in detailed household surveys administered in the wet and dry seasons. Figure 3-1 shows the socio-economic status (SES-2) distribution of households across each of the four data collection activities. The corresponding population size (N) or sample size (n) is also provided. It is important to note that the sample size is insignificant to extrapolate the findings to any level beyond the communities where the data were collected.

The data on household size and water usage (Table 3-5)[10] shows there is a noticeable difference between the averages for the census and the detailed household surveys in both the wet (HH Wet) and dry (HH Dry) seasons. The average household size is considerably smaller in the census as compared to the detailed household surveys. This could be because the household

[10] Water usage data from each survey was analyzed and extreme outliers were removed following accepted methods (Tabachinick and Fidell, 2007). The following number of surveys was removed from each source: 23 HH Dry, 20 HH Wet, and 296 Census.

surveys in the dry and wet season Non-poor (NP) households, which are typically smaller, were under-represented and Very Poor (VP) households, which are typically larger, were over-represented (see Figure 3-1).

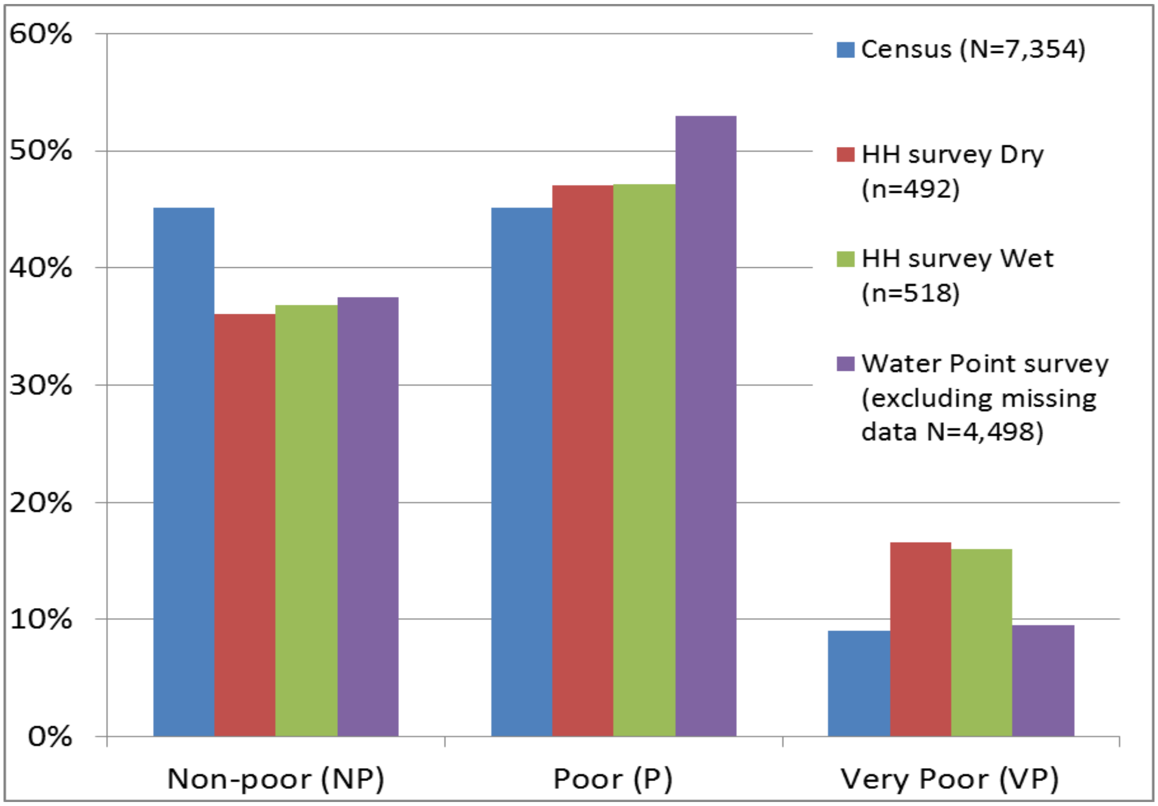


Figure 3-1 Socio economic status of households in Burkina Faso by data collection tool. Data from comprehensive census, Water Point Surveys, and Household (HH) surveys during the dry and wet seasons are also shown.

The difference in water usage between the census (conducted in the dry season) and the detailed household survey from the dry season is likely attributable to the difference in how the data were obtained in the respective surveys. Respondents in the census were asked to directly estimate the average amount of water collected each day, while in the detailed household survey the respondents were required to review the type and number of containers used to collect water each day. The later survey was more in-depth and involved several triangulation questions that were used to validate responses.

Table 3-5 Household size and per person daily water usage.

Data Source		Household size (persons/household)		Water Usage (L/person/day)	
		Average	SD Dev.	Average	SD Dev.
Rural	Census	6.7	4.8	27.0	14.2
	HH Dry	8.9	5.0	39.8	25.0
	HH Wet	8.8	5.0	28.4	24.5
Peri Urban	Census	5.5	3.8	33.7	15.9
	HH Dry	6.6	3.6	43.8	25.0
	HH Wet	6.7	3.1	41.1	23.6

Comparing the HH Dry and HH Wet data the only statistically significant difference observed was for water usage in rural areas during the wet season ($p=0.001$). This was expected as a rural household can more easily access informal water sources which are more abundant during the wet season, and hence would withdraw less water from formal water sources. Overall, households were 19 times more likely to cite informal sources as their primary source in the wet season (39 of 430 households) versus in the dry season (2 of 422 households).

The average household size, annual household expenditure, and annual household income broken down by socio-economic status (SES-2) are summarized in Table 3-6. These user-reported values are taken from the detailed household surveys from the dry season (HH dry). Average expenditures and income were as expected; that is, Non-poor (NP) > Poor (P) > Very Poor (VP). Average annual reported income was much greater in NP households compared to the average expenditures for the same households. It is also important to note that the average annual expenditures were greater than average annual income for the VP households. Comparing the median expenditures and incomes to socio-economic status suggests that the qualitative classification system used here (SES-2) is valid.

Table 3-6 Average household size and annual household expenditure and income. Data is from study sites in in Burkina Faso and is separated by socio-economic status. Data was obtained from detailed household survey done in the dry season (HH Dry). Expenditure and income units are US$/household/ year.

Socio-economic Status (SES-2)	Household Sample Size	Household Size		Expenditure (Exp_TOT)		Income (Rev_TOT)	
		Rural	Peri-Urban	Median	Mean	Median	Mean
Non-poor (NP)	183	10.3	6.8	$1,224	$1,266	$1,047	$2,332
Poor (P)	232	8.7	6.5	$696	$861	$687	$1,109
Very Poor (VP)	77	7.2	6.2	$354	$709	$501	$577
All	492	8.9	6.6	$716	$983	$755	$1,463

The average houshold expenditures on water from the detailed housheold surveys (HH Wet and HH Dry) are summarized in Table 3-7. Conversely to CAPEX and CAPMANEX which did not vary seasonally, OPEXfin and OPEXecon were found to vary between the wet and dry season as shown by the data. These expenditures are lower in the wet season when water is more readily available from rainwater and/or traditional sources and hence expenditure on formal sources may decrease.

Table 3-7 Average per person expenditures made by households in Burkina Faso. Expenditures are by WASHCost category during the dry and wet seasons (Source: Dry and Wet Season Household Surveys). The statistical significance of the difference between the seasonal means is shown along with the equation reference number.

Eqn #	Cost Category	Unit	Dry	Wet	Sig (2-
3.1	**CAPEX**	US$/person	$1.5		N/A
3.4	**CAPMANEX**	US$/person/year	$2		N/A
3.3	**$OPEX_{FIN}$**	US$/person/year	$9.5	$7.5	0.025
3.6	**$OPEX_{ECON}$**	US$/person/year	$9	$5	0.000
3.5	**Financial_EX**	US$/person/year	$12	$10	0.003
3.7	**Cumulative_EX***	US$/person/year	$19.5		N/A

*Sector 1 data was not included in the calculation of these average expenditures.

CAPEX is on average US$1.5[12] per person and the average capital maintenance expenditure (CAPMANEX) is US$2 per person per year. These expenditures are very low compared to the other expenditure categories. Only one third of households (n=183) reported

[12] All expenditure data was collected in West African Francs and converted to US dollars. Expenditures are reported in USD and rounded to the nearest half dollar.

making a contribution to the installation of a water system (CAPEX). Similarly, only one third of households made some additional contribution to renew or replace a water system (n=160). Most CAPMANEX concerns household investment in transportation and storage containers.

A summary of the average financial expenditures on water, disaggregated by socio-economic status as described in the research (SES-2), is shown in Table 3-8. The remaining sections will continue to explore the relationships between these household expenditures, socio-economic status and other variables such as seasons, rural-peri-urban differences, and service levels.

Table 3-8 Average per person expenditures on water by socio-economic status. Source: Dry and Wet Season Household Surveys.

Socio-economic Status (SES-2)	CAPEX[1] US$/person	CAPMANEX[1] US$/per-yr.	OPEXfin[1,2] US$/per-yr.	Financial_EX[1,2] US$/per-yr.
Non-poor (NP)	$2.5	$2.5	$8.5	$11
Poor (P)	$1	$2	$8.5	$10.5
Very Poor (VP)	$2	$2	$8.5	$11
All	$1.5	$2	$8.5	$11

[1]Source:Dry season household surveys. [2]Source:Wet season household surveys.

3.4.2 Correlation Analysis of Household Expenditures

To understand the relationships between household expenditures and additional variables included in the research (e.g. household size, location) a correlation analysis was performed. Although correlation analysis does not determine causation, it is starting point for building multivariate regression models that can help isolate effects of multiple variables from one another and help determine causation (for a full presentation of results, see Appendix F). For a better understanding of causal effects and to isolate the effects of potential confounding variables, multivariate regression analyses were used. Those results are presented in Section 3.4.3.

3.4.2.1 Household Size

In the sample communities, household size was positively correlated, at the 99 per cent confidence level, to water usage. Larger households consumed more water as a household (r=.36, C1[13]) but less on a per person basis (r=-.28, B1). Correspondingly these households had higher financial costs as a household[14] but lower per person financial (r=-.15, I1), economic (r=-.26, N1), and cumulative (r=-.3, O1) costs than households with fewer members.

3.4.2.2 Source Distance

Households whose primary water point was further away also had a secondary water point that was further away (r=.5, K10). However, when comparing water point preference and distance for all formal water points available to households, the data suggests that distance is not the only factor that influences preference. As can be observed from Figure 3-2, the first preferred water point for 38 per cent of the households was not the closest. From the correlation analysis the further the preferred water point the greater the number of trips made to it (r=.1, L10). As the distance travelled increases the quantity of water that may be carried on any single trip decreases and therefore more trips will be required to transport the same total quantity of water.

Households with a closer primary source had higher per person financial operating expenditure (r=-.12, I10), while those households whose primary sources were further dedicated more time to water collection and hence had higher per person opportunity costs (r=.14, N10).

[13] The first value listed is the correlation coefficient (r) and the second is the cell reference. See Appendix F for a description of the cell referencing system. Table in Appendix F contains a list of the correlation coefficients (r) and a definition of correlation strength.
[14] Household expenditure (e.g. Financial_TOT) are not included in Table in Appendix F.

The seasonal difference in average distance from the household to the water source was greater for secondary water points (see Table 3-9).

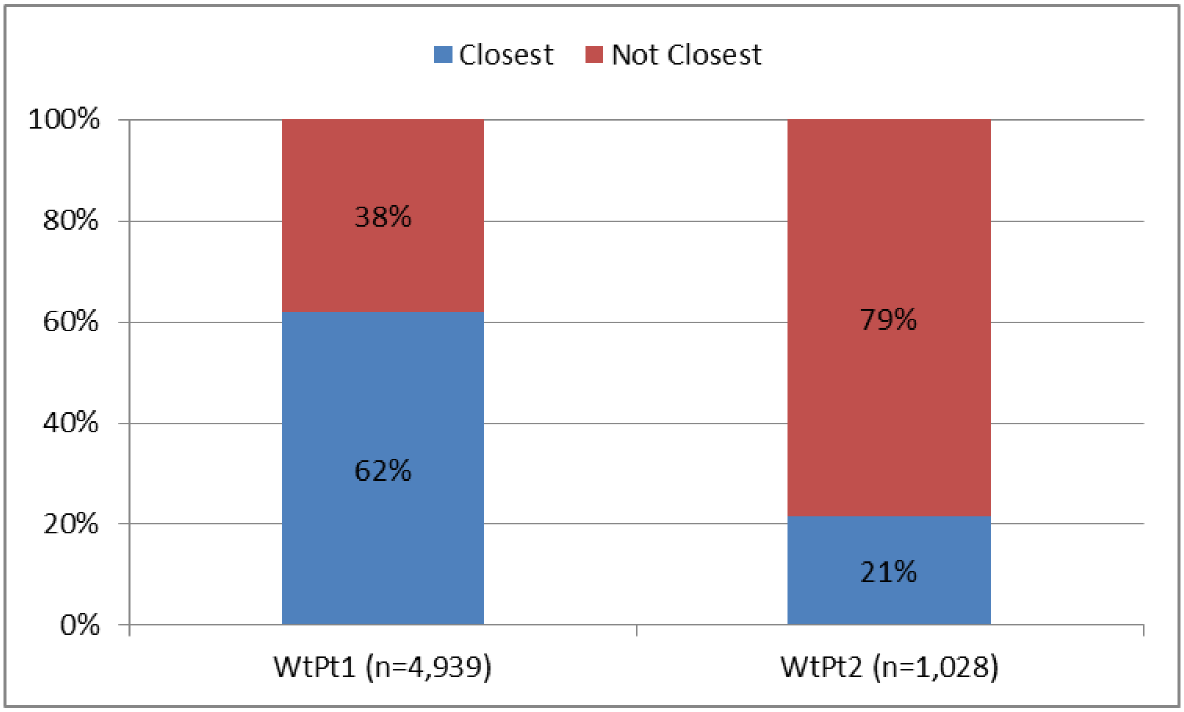


Figure 3-2 Water point preference and distance from the home (Source: census data). Households were only asked to list their primary (WtPt1) and secondary (WtPt2) water points. Sufficient data was available to compare distance to water point preference for 4,939 households (WtPt1) and 1,028 households (WtPt2).

Table 3-9 Average distance from household to water source by season. Sample size (n) is shown in parenthesis.

Preferred Water Point	Wet Season (meters)	Dry Season (meters)
WtPt1	369 (n=390)	352 (n= 417)
WtPt2	355 (n= 66)	575 (n= 131)

3.4.2.3 Water Usage

As previously mentioned, household water use was found to be greater in larger households. Conversely, per person water use was lower in larger households. Both household water use and per person water use were positively correlated to total household income (r=.1, B4 and r=.15, C4 respectively) and expenditure (r=.1, B5 and r=.22, C5 respectively). This trend between income and water use has been well documented in the developed world (Mihelcic and Zimmerman, 2010). Per person water use is positively correlated to the WASHCost cost categories of CAPMANEX (r=.22, B7) and OPEX (financial and economic). In other words, expenditure per person on water increases with the quantity of water used per person.

3.4.2.4 Household Income and Expenses

Households with higher annual reported income invested more in capital expenditure (CAPEX) than households with lower income. Household income was also positively correlated to per person financial operating expenditures. Households with less reported income and expenditures used less water and had higher per person opportunity costs or OPEXecon than households who reported higher income and expenditures.

3.4.3 Inter-variable Effects of Household Expenditures

To determine how household expenditure - financial, economic, and cummulative on formal water sources is related to or influenced by factors such as socio-economic status, season, water service levels (e.g. quantity, quality, distance and crowding), or other factors, it is necessary to conduct multivaritate analyses. These analyses can help isolate the influence of each variable from the possible confounding effects of other variables. This section will explore the effects of socio-economic status, development, household size, and season on expenditures.

Inter-variable effects were controlled by performing a linear regression analysis of the data. The independent or predictor variables (e.g. household size, rural or peri-urban, and socio-economic status) are entered into an equation that is designed to predict the value of the dependent variable (e.g. CAPEX, OPEX). Standard linear regression analysis involves minimizing the sum-of-squared differences between a response (dependent) variable and a weighted combination of predictor (independent) variables. The estimation coefficients (β values) reflect how changes in the predictor variables affect the response variable.

Table 3-10 Linear regression analysis results. The units of each estimation coefficients (β value) are equal to the units of the dependent variable (parentheses in the first column). The p-values (parentheses in the model parameters) describe statistical significance of each relationship. Statistically significant values are shaded.

Row	Dependent variable (units)	Independent Variables (p-values)				
		Constant β_0	Very Poor β_1	Rural β_2	Dry β_3	HH_size β_4
1	**Financial_prctg_rev** (%)	1.1% (.888)	11.7% (.143)	21.2% (.001)**	NA	0.5% (.431)
2	**Financial_prctg_exp** (%)	1.5% (.649)	8.3% (.016)*	7.4% (.008)**	NA	0.5% (.064)
3	**OPEXecon_TOT** (US$/HH/yr.)	$42.5 (.000)**	-$24 (.011)*	$12 (.158)	$23 (.001)**	-$2.5 (.002)**
4	**OPEXecon_prctg_rev** (%)	3.7% (.000)**	1.5% (.023)*	3.5% (.000)**	2.5% (.000)**	-0.4% (.000)**
5	**OPEXecon_prctg_exp** (%)	6.1% (.000)**	0.8% (.617)	5.9% (.000)**	4.1% (.001)**	-0.6% (.000)**
6	**Cumm_prctg_rev** (%)	14.3% (.165)	11.7% (.260)	35.4% (.000)**	NA	-0.2% (.819)
7	**Cumm_prctg_exp** (%)	15.9% (.004)	13.9% (.014)*	19.4% (.000)**	NA	-0.4% (.450)

*. Relationship is significant at the 0.05 level (2-tailed), or 95 per cent significance.
**. Relationship is significant at the 0.01 level (2-tailed), or 99 per cent significance.
†. In order to include household size in models absolute expenditure are shown as US$ per household (i.e.- "TOT")
Note: Only Very poor was included as a model parameter as there was no statistically significant difference between Poor and Non-poor households. Sector 1 data was excluded for those variables that are calculated using GIS data (e.g. OPEXecon , Cumm_TOT, etc).

For example, in Table 3-10, increasing the household size by one person while holding all other independent variables constant (i.e. household with same socio-economic status, location, and season) will result in a decrease of the household economic expenditures by approximately US$2.5 (i.e. the value of β_4 of OPEXecon_TOT, Row 3) for the household over the course of the year (i.e. β_4 has units of US$/household/year). In this case the increase is statistically significant to the 99.8 per cent (or 1 minus the "p- value"). Similarly, if you look at the same household between the dry and wet seasons (i.e. holding all the other parameters constant but the season) you will see that, during the dry season OPEXecon_TOT expenditures increase US$3 per household per year (β_3). The units of the estimation coefficients (β values) are the same units as the response (dependent) variable, which is shown in parentheses in the second column of Table 3-10. Note that for household economic expenditure there is a statistically significant difference between Very Poor and Non-poor or Poor households (Row 3, β_1 p-value = .011). All model parameters that are statistically significant (i.e. p-values less than 0.05) are shaded in the Table 3-10 and all other subsequent tables presenting regression models.

After controlling for household size and rural-peri-urban effects it appears that socio-economic status, as defined qualitatively in this study (SES-2), has no effect on ABSOLUTE financial expenditures (CAPEX, CAPMANEX, or $OPEX_{FIN}$)[15]. However there is a difference in these expenditures RELATIVE to their household income and household expenditures, as shown in Table 3-10. Considering expenditures on water as a percentage of total reported annual income (i.e. those variables with"_prctg_rev" suffixes) or total reported expenditures (i.e. those variables with"_prct_exp" suffixes) there is a statistically significant influence of the socio-economic status. Table 3-18 shows that all households have financial expenditures between US$10.5 and US$11 per person per year, yet Table 3-11 shows that, on average, NP household income is 3.5 times higher than that of VP households. When controlling for household size, rural-peri-urban effects, and seasonality, the difference in expenditures between Very Poor (VP) and other households (i.e. Non-poor (NP) and Poor (P)) is statistically significant. What VP households spend on water represents 8.3 per cent (p=0.016) more of their total household expenses as compared to NP and P households. It is important to note, this is not an 8.3 per cent difference in the actual financial expenditure, but rather an 8.3 per cent difference in the relative expenditures (i.e. financial expenditure divided by the total annual expenses for that household). However, the differences between P and NP households with regard to Financial_prctg_exp are

[15] Results not presented here.

not statistically significant. With regard to annual household income the relative expenditure (Financial_prctg_rev in Table 3-10) difference between VP and P/NP was not statistically significant (i.e. the p value was greater than 0.05).

Therefore it is concluded that the financial expenditure in water (US$/person/yr.) as a percentage of total reported expenditures (US$/person/yr.) is greater for VP households as compared to households of higher socio-economic status. In addition, although the expenditures on water by VP households represent a significantly greater percentage of their total household expenses as compared to P or NP, no such difference is discernible between P and NP. The average values for financial expenditures on water as a percentage of total income and total expenditures across socio-economic categories and all households included in the study is shown in Table 3-11.

Table 3-11 Average income, expenses, and recurrent financial expenditures on water. Data is shown as a percentage of income and expenses for different socio-economic categories. (Source: Dry and Wet Season Household Surveys).

Socio-economic Status (SES-2)	Income* (US$/per-yr.)	Expenses* (US$/per-yr.)	$OPEX_{FIN}$**		Financial_EX**	
			% Income	% Expenses	% Income	% Expenses
Non-poor (NP)	$356	$192	12%	10%	20%	15%
Poor (P)	$183	$137	18%	11%	25%	14%
Very poor (VP)	$108	$130	28%	19%	37%	23%
All	$233	$156	17%	12%	25%	16%

Table 3-12 shows the economic expenditures by socio-economic category used in this research. The difference in time dedicated to collecting water between socio-economic groups is statistically significant for the primary and secondary water points but not for the tertiary water point or overall. On average VP households dedicate 21 minutes per person per day to collecting water, compared to NP households that spend on average only 14 minutes per person per day. However, due to the higher value of time of NP households compared to P and VP, and P compared to VP, the average economic expenditures on water are lowest in VP households at US$6/person/day (See Table 3-12). Controlling for effects of rural-peri-urban areas, seasons, and household size VP households spend US$24/household/year less than NP or P households (See Table 3-10).

However in terms of economic expenditure relative to total household income (OPEXecon_prctg_rev from Table 3-10), Very Poor (VP) expenditures are 1.5 per cent greater compared to Poor (P) and Non-poor (NP) (see Table 3-10, column 3 for the row OPEXecon_prctg_exp).

Table 3-12 Average household economic expenditures for collecting water. (Source: Dry and Wet Season Household Surveys).

Socio-economic Status (SES-2)	$OPEX_{ECON}$ (US$/person-year)	Time Dedicated to Collecting Water (minutes/day/person)			
		WtP1t	WtPt2	WtPt3	All Water Points
Non-poor	$7.5	7.8 (3.1)	5.6 (3.6)	3.2 (0.8)	13.5 (8.5)
Poor	$7.5	9.8 (3.5)	9.4 (5.7)	11.5 (11.5)	15.3 (8.7)
Very poor	$6	12.3 (4.5)	20.7 (7.9)	6.7 (6.7)	21.1 (9.8)
All	$7.5	9.6 (3.5)	9.6 (4.4)	5.4 (3.9)	15.8 (8.8)

As described in Section 3.3.4.3, the cumulative expenditures on water were determined from the financial ($OPEX_{FIN}$) and economic ($OPEX_{ECON}$) expenditures from both the wet and dry season surveys. Comparing these cumulative expenditures to the reported expenses of each household, a statistically significant difference between Very Poor (VP) households and the others was discovered. As a percentage of total household expenses, the cumulative expenditure on water for an average Very Poor (VP) household is 13.9 per cent higher than for Poor (P) or Non-poor (NP) households, all else being equal (i.e. season, household size, rural-peri-urban). Similarly to the relative financial expenditures there was no statistically significant difference between VP and NP/P when considering cumulative expenditures relative to household income (Cumm_prctg_rev). Also there was no statistically significant difference between NP and P households. Therefore we can conclude that, similarly to the financial expenditures on water, the cumulative household expenditure on water as a percentage of total reported expenses (US$/person/year) is greater in Very Poor (VP) households compared to Non-poor (NP) and Poor (P) households.

3.4.4 Level of Development, Season, and Household Size

The previous section demonstrated that socio-economic status did not affect absolute household financial and cumulative expenditures on water, but did impact the absolute economic expenditures as well as the relative expenditures (finanical, economic, and cumulative) on water. The effects of the level of development (rural vs peri-urban), season, and household size were all statistically significant in terms of absolute expenditures (see Table 3-13). Similar to Table 3-10, the beta values (β) shown in Table 3-13 display the change in the dependent variable for a relevant change in one of the model parameters (i.e. socio-economic status, season, development (rural vs peri-urban), or household size), while holding the other parameters constant. For example, controlling for socio-economic class, seasonality and household size, rural households (fifth column) pay approximately US$17.5 per household per year less in financial operating expenditures than peri-urban households (i.e. β_2 value for Row 3: $OPEX_{FIN}$_TOT). All financial recurrent expenditure considered, rural households pay US$17 per household per year less than peri-urban households (β_2 value for Row 4). After contolling for the socio-economic class, season, and household size the difference in economic expenditures ($OPEX_{ECON}$) between rural and peri-urban areas is not significant (β_2 p-value for Row 5 is greater than 0.05). However, the difference in time dedicated to water collection is greater by 81 minutes per household per day in rural areas compared to peri-urban areas after controlling for season, socio-economic class, and housheold size (β_2 value for Row 7).

Controlling for rural-peri-urban development and household size, households pay approximately US$18 per houshold per year more in $OPEX_{FIN}$ during the dry season verses the wet season (β_3 value Row 3). The increase in economic expenditure between the dry and wet season is larger, US$23 ($\beta_3$ value Row 5).

Finally, looking at household size (β_3) and controlling for seasonal and development changes, if a household were to have an additional member they could expect to pay US$5 per household per year more in $OPEX_{FIN}$ but $2.5 per household per year less in $OPEX_{ECON}$. This means that larger households paid more, as a household, in both financial terms but less in economic operation costs, with a cumulative recurrent cost of US$5.5 per household per year for each additional member.

Table 3-13 Development, season and household size effects on household expenditures. The statistically significant values are shaded.

Row	Dependent variable (units)	Independent Variables (p-values)				
		Constant β_0	Very Poor β_1	Rural β_2	Dry β_3	HH_size β_4
1	**CAPEX_TOT**[†] (US$/HH	$9 (.256)	$5 (.569)	$10.5 (.148)	NA	-$0.5 (.701)
2	**CAPMANEX_TOT** (US$/HH/yr.)	$3.5 (.083)	-$3 (.204)	$2.5 (.159)	NA	$1.5 (.000)**
3	**OPEXfin_TOT** (US$/HH/yr.)	$23.5 (.006)**	$2 (.846)	-$17.5 (.017)*	$18 (.008)**	$5 (.001)**
4	**Financial_TOT** (US$/HH/yr.)	$38.5 (.000)**	-$0 (.985)	-$17 (.040)*	NA	$6.5 (.000)**
5	**OPEXecon_TOT** (US$/HH/yr.)	$42.5 (.000)**	-$24 (.011)*	$12 (.158)	$23 (.001)**	-$2.5 (.002)**
6	**Cumm_TOT** (US$/HH/yr)	$95.5 (.000)**	$28 (.061)	$3 (.830)	NA	$5.5 (.000)**
7	**Collxn_time** (mins/HH/day)	-7.7 (.623)	-3.7 (.805)	81.3 (.000)**	56.6 (.000)**	3.3 (.007)**

3.5 Analysis of Household Expenditures Against Service Levels

In order to analyze the relationship between expenditures and level of service received, as measured by the WASHCost service level indicators for Burkina Faso (see Table 3-4), two different regression analyses were performed. For the service level indicators that are determined only by continuous variables (i.e. quantity of water and distance to water source) a linear regression was performed as previously described in Section 3.4.3. For the indicators that are ordinal in nature (i.e. water quality monitoring and crowding[16]) ordinal regressions were performed. In addition an ordinal regression was performed for the overall service level which is a function of Water Quantity, Water Quality Monitoring, and Accessibility (distance and crowding). For more on the results and the interpretation of ordinal regression models see Appendix G.

3.5.1 Overview

According to this research and consistent with methods used in WASHCost, each household received an overall service level score by identifying the lowest individual indicator score. The following example demonstrates how this is done. A hypothetical household is considered, with access to a single water source that is: 1) close by (i.e. Distance =High), 2) monitored frequently (i.e. Water Quality Monitoring = High), and 3) has few people using it (i.e. Crowding = High). However, if the source can only provide less than 20 liters/person/day (i.e. Quantity = Sub-standard) the overall service received by this household is actually Sub-standard. Table 3-14 shows a breakdown of the communities by service level category for each of the four

[16] Although the Accessibility Crowding indicator is based upon observed and design populations, which are both continuous variables, it is more easily analyzed as an ordinal variable because each individual water supply technology has a different design population.

indicators as well as overall service. 72% of households do not have a basic level of service, 333 receiving a sub-standard level of service and 255 no service at all.

Table 3-14 Overall service levels by household. Source: Dry and wet season household surveys, excluding Sector 1 data.

<table>
<tr><th>Service Level Category</th><th>Quantity</th><th>Water Quality Monitoring*</th><th>Distance</th><th>Crowding</th><th>Overall Service*</th></tr>
<tr><td>High</td><td>109</td><td>262</td><td>17</td><td rowspan="3">499</td><td>3</td></tr>
<tr><td>Intermediate</td><td>107</td><td rowspan="3">360</td><td rowspan="3">693</td><td>94</td></tr>
<tr><td>Basic</td><td>300</td><td>130</td></tr>
<tr><td>Sub-Standard</td><td>285</td><td rowspan="2">316</td><td>333</td></tr>
<tr><td>No Service</td><td>14</td><td>192</td><td>105</td><td>255</td></tr>
<tr><td>DM</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td></tr>
</table>

*Primary and secondary water points were considered in the scoring. The lower value was used in the case of Water Quality Monitoring.

The model describing the influence of different variables on overall service levels can be found in Table G-5 in Appendix G. Controlling for rural-urban development, seasons, and socio-economic status households with higher financial expenditure (p=0.000) had higher overall service level scores. Rural households had lower service levels than peri-urban households (p=0.012).

Table 3-15 Household service level categories segregated by rural and peri-urban areas (shown as a percentage). Source: Dry and wet season household surveys, excluding Sector 1 data.

<table>
<tr><th rowspan="2">Service Level Category</th><th colspan="2">Quantity</th><th colspan="2">Water Quality Monitoring*</th><th colspan="2">Distance</th><th colspan="2">Crowding</th><th colspan="2">Overall Service*</th></tr>
<tr><th>Rural</th><th>Peri-Urban</th><th>Rural</th><th>Peri-Urban</th><th>Rural</th><th>Peri-Urban</th><th>Rural</th><th>Peri-Urban</th><th>Rural</th><th>Peri-Urban</th></tr>
<tr><td>High</td><td>16%</td><td>6%</td><td>14%</td><td>88%</td><td>1%</td><td>4%</td><td rowspan="3">61%</td><td rowspan="3">61%</td><td><1%</td><td><1%</td></tr>
<tr><td>Intermediate</td><td>16%</td><td>5%</td><td rowspan="3">57%</td><td rowspan="3">5%</td><td rowspan="3">83%</td><td rowspan="3">90%</td><td>13%</td><td>6%</td></tr>
<tr><td>Basic</td><td>35%</td><td>41%</td><td>15%</td><td>19%</td></tr>
<tr><td>Sub-Standard</td><td>31%</td><td>48%</td><td rowspan="2">39%</td><td rowspan="2">39%</td><td>35%</td><td>59%</td></tr>
<tr><td>No Service</td><td>2%</td><td><1%</td><td>29%</td><td>7%</td><td>15%</td><td>6%</td><td>37%</td><td>15%</td></tr>
</table>

*Primary and secondary water points were considered in the scoring. The lower value was used in the case of Water Quality Monitoring.

Table 3-15 shows a breakdown of the service level scores for rural and peri-urban areas. This table demonstrates that rural households generally have higher service levels for water quantity but fare poorly compared to their peri-urban counterparts for water quality monitoring and distance to their source.

Table 3-16 Peri-urban households service levels segregated by socio-economic status. Source: Dry and wet season household surveys, excluding Sector 1 data.

<table>
<tr><th rowspan="2">Service Level Category</th><th colspan="3">Quantity</th><th colspan="3">Water Quality Monitoring*</th><th colspan="3">Distance</th><th colspan="3">Crowding</th><th colspan="3">Overall Service*</th></tr>
<tr><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th></tr>
<tr><td>High</td><td>12%</td><td>4%</td><td>0%</td><td>73%</td><td>94%</td><td>100%</td><td>9%</td><td>2%</td><td>0%</td><td rowspan="3">71%</td><td rowspan="3">53%</td><td rowspan="3">68%</td><td>2%</td><td>1%</td><td>0%</td></tr>
<tr><td>Intermediate</td><td>11%</td><td>3%</td><td>0%</td><td rowspan="3">11%</td><td rowspan="3">4%</td><td rowspan="3">0%</td><td rowspan="3">89%</td><td rowspan="3">90%</td><td rowspan="3">93%</td><td>15%</td><td>3%</td><td>0%</td></tr>
<tr><td>Basic</td><td>36%</td><td>43%</td><td>39%</td><td>18%</td><td>18%</td><td>25%</td></tr>
<tr><td>Sub-Standard</td><td>39%</td><td>50%</td><td>61%</td><td rowspan="2">29%</td><td rowspan="2">47%</td><td rowspan="2">32%</td><td>45%</td><td>65%</td><td>68%</td></tr>
<tr><td>No Service</td><td>2%</td><td><1%</td><td>0%</td><td>17%</td><td>3%</td><td>0%</td><td>2%</td><td>8%</td><td>7%</td><td>19%</td><td>14%</td><td>7%</td></tr>
</table>

*Primary and secondary water points were considered in the scoring. The lower value was used in the case of Water Quality Monitoring.
NP-Non-poor; P-Poor; VP-Very Poor

Table 3-17 Rural households service levels segregated by socio-economic status. Source: Dry and wet season household surveys, excluding Sector 1 data

<table>
<tr><th rowspan="2">Service Level Category</th><th colspan="3">Quantity</th><th colspan="3">Water Quality Monitoring*</th><th colspan="3">Distance</th><th colspan="3">Crowding</th><th colspan="3">Overall Service*</th></tr>
<tr><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th><th>NP</th><th>P</th><th>VP</th></tr>
<tr><td>High</td><td>17%</td><td>16%</td><td>14%</td><td>13%</td><td>13%</td><td>16%</td><td>3%</td><td>1%</td><td>0%</td><td rowspan="3">63%</td><td rowspan="3">61%</td><td rowspan="3">59%</td><td>1%</td><td>0%</td><td>0%</td></tr>
<tr><td>Intermediate</td><td>17%</td><td>17%</td><td>12%</td><td rowspan="3">56%</td><td rowspan="3">56%</td><td rowspan="3">62%</td><td rowspan="3">82%</td><td rowspan="3">82%</td><td rowspan="3">88%</td><td>12%</td><td>13%</td><td>17%</td></tr>
<tr><td>Basic</td><td>36%</td><td>31%</td><td>45%</td><td>15%</td><td>13%</td><td>20%</td></tr>
<tr><td>Sub-Standard</td><td>27%</td><td>34%</td><td>28%</td><td rowspan="2">37%</td><td rowspan="2">39%</td><td rowspan="2">41%</td><td>34%</td><td>36%</td><td>33%</td></tr>
<tr><td>No Service</td><td>2%</td><td>2%</td><td>1%</td><td>31%</td><td>31%</td><td>22%</td><td>15%</td><td>17%</td><td>13%</td><td>38%</td><td>39%</td><td>30%</td></tr>
</table>

*Primary and secondary water points were considered in the scoring. The lower value was used in the case of Water Quality Monitoring.
NP-Non-poor; P-Poor; VP-Very Poor

Compared to Non-poor and Poor, the Very Poor generally had lower overall service levels ($p=0.013$, see Table G-5, Appendix G). When analyzing socio-economic status disaggregated by rural and peri-urban areas, the peri-urban Non-poor (NP) households have higher overall service levels than all other households ($p=0.056$)[17]. Table 3-16 and 3-17 show the service levels disaggregated by socio-economic status for urban and rural areas respectively. Over 17 per cent of urban Non-Poor households have intermediate or high overall service levels

[17] Model is not shown here.. Peri-urban Non-poor was substituted for "rural" in Table G-5 in Appendix G.

(see Table 3-16). The Non-Poor in peri-urban areas also have higher service levels with regard to the water quantity indicator and accessibility, both distance and crowding.

The costs for accessing different overall service levels can vary greatly. Financial expenditures (Financial_EX) range between $9 per person per year for households with no service to $38 per person per year for those with high service (See Table 3-18). Households with no service spend, on average, more on $OPEX_{ECON}$ than households with sub-standard and basic service. As a result, the households with no service spend more overall (Cumm_EX) than those with sub-standard service and nearly as much as those households with basic service.

Table 3-18 Average costs by overall service level. Source: Dry and wet season household surveys, excluding Sector 1 data.

Service Level Category	CAPEX (US$/per)	Recurrent expenditure				
		CAPMANEX (US$/per/yr)	OPEXfin (US$/per/yr)	OPEXecon (US$/per/yr)	Financial_EX* (US$/per/yr)	Cumm_EX** (US$/per/yr)
High	$3	$1	$37	$10	$38	$36
Intermediate	$4	$3.5	$17	$12	$20	$32
Basic	$3.5	$2	$8	$6	$10.5	$20.5
Sub-Standard	$0.5	$2	$8	$6.5	$10	$16
No Service	$1.5	$2	$6	$7.5	$9	$18.5

*Financial_EX = CAPMANEX + $OPEX_{FIN}$, see equation 3.5.
** Cumm_EX = Financial_EX + $OPEX_{ECON,}$ see equation 3.7.

When analyzing the recurrent cost of service levels disaggregated by socio-economic status, we can see that the cost of each service level varies across poverty categories. Figures 3-3a, 3-3b, and 3-3c show the average annual per person financial, economic, and cumulative costs for each service level disaggregated by socio-economic status, respectively.

Figures 3-3a, 3-3b, and 3-3c show that Very Poor (VP) households with No Service or Basic service pay more than Non-poor households. This is the case for the financial expenditures (Figure 3-3a) for those receiving intermediate and basic service. Very Poor (VP) households have significantly higher opportunity costs and cumulative expenditures to access intermediate services. In general, Figures 3-3a, 3-3b, and 3-3c show that there are significant financial and economic costs to improve service levels from basic to intermediate service.

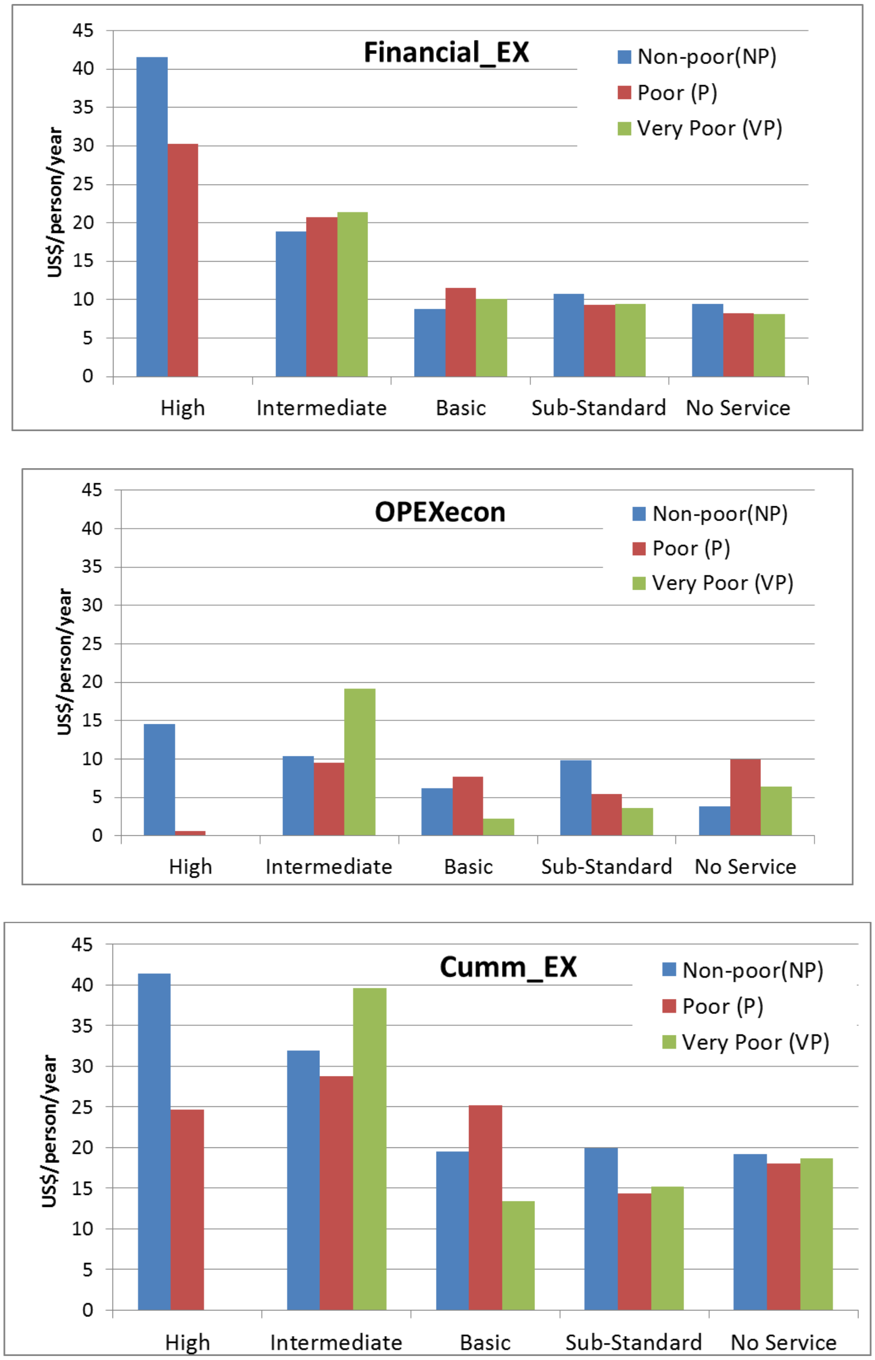


Figure 3-3 Expenditure on water by service level and socio-economic status. (a) (Top) Financial expenditures. (b) (middle) Economic expenditure. (c) (Bottom) Cumulative expenditures. Source: Dry and wet season household surveys, excluding Sector 1 data.

Financial expenditures seem to be driven by the service level as absolute financial expenditures are, in general, very similar for a given service level across poverty categories (with the exceptions noted earlier). The trend that seems consistent within each figure is the significant increase in expenditures to go from basic to intermediate. Table 3-19 has the average costs to ascend each step on the service ladder (i.e. from basic to intermediate service).

Table 3-19 Cost between service levels segregated by socio-economic status. Costs are average annual per person financial costs and all units are US$/person/year. Source: Dry and wet season household surveys.

Difference between Overall Service Levels	Annual per person Financial Expenditures		
	Non-Poor (NP)	Poor (P)	Very Poor (VP)
Intermediate to High	$22.72	$9.46	NA
Basic to Intermediate	$10.08	$9.21	$11.31
Sub-Standard to Basic	$-1.92	$2.22	$0.62
No Service to Sub-Standard	$1.26	$1.05	$1.32

Conversely to financial expenditure, economic expenditure decreases in general when the level of service improves, for all household categories (see Figure 3-3b). The higher the level of service received the less time and effort that needs to be dedicated to collecting, transporting and storing water. However, often the households with the higher levels of service with regard to accessibility distance (i.e. those with private connections) may also have higher value of income. Thus for the same amount of time dedicated to water collection, their economic expenditure is considered higher. This is why the economic expenditure of the Non-poor households receiving high levels of service is so high. In general if the $OPEX_{ECON}$ value in Figure 3-3b is high for Very-Poor households it represents a greater investment of time, while in general higher $OPEX_{ECON}$ expenditures for NP households means greater value of time (see Table 3-20).

The annual per person costs for water supply technologies used in the 9 communities in Burkina Faso are shown below in Table 3-20. The technologies designed to provide higher service levels (i.e. private connections) require higher financial contributions but lower time investments. Households with private connections or accessing standpipes spent, in financial terms, three times as much per person per year than those accessing handpumps. However households with private connection benefited from the close proximity of their water source and invested six times in terms of time to collect, transport, store water, than households with handpumps. This has significant implications with regard to time poverty for poor households, and when considering the relative financial contributions made by poor households to access the same service levels there is a greater impact on the household budget.

Table 3-20 Financial and economic expenditures by technology. Only the primary water point is considered. Sample size is shown (N). Source: Dry and wet season household surveys excludes Sector 1 data.

Water Supply Technology	N	Financial_EX (US$/per/yr)	Opportunity Costs of Water Collection		
			OPEXecon (US$/per/yr)	Time Investment (min/day-per)	Value of Time (CFA/per-hr.)
Private connection	16	$23.5	$9.5	2.4	88
Standpipe	323	$15	$7.5	4.0	57
Handpump	382	$8	$7.5	14.5	29

3.5.2 Inter-variable Effects of Water Service Indicators

3.5.2.1 Water Quantity

Using data from the household surveys a linear model was created (R^2=0.310) to understand the effects of different variables on the quantity of water consumed from each water source. Table 3-21 shows the model with the statistically significant variables.

Table 3-21 Effects of expenditures on water quantity.

Dependent variable (units)	Model parameters (p-values)[1]							
	Constant β_0	OPEXecon (CFA) β_1	Financial_EX (CFA) β_2	Wtpt1_dist (meter) β_3	HH_size (members) β_4	Non-poor β_5	Dry β_6	Rural β_7
Water use (lpcd)	37.674	3.95x10^{-4}	0.001	-0.016	-1.099	5.920	5.952	-6.647

Controlling for total time dedicated for water collection, distance to primary source, seasonal variability, rural-peri-urban differences, and socio-economic status, households that had higher per person expenditures (Financial_EX) receive more water per person (see Table 3-21). Households that spend an additional 1,000 CFA (US$2) per year per person receive an extra liter of water per person per day. Investing in the Financial_EX would mean the implied marginal financial cost of a cubic meter of water (1,000 liters) is 2,740 CFA (US$5.45). Investing 1,000 CFA (US$2) in CAPEX would provide an extra liter of water per person per day. A primary source that is located 100 meters further away from the household would result in 1.6 liters less per person per day.

Across all surveyed communities Non-Poor households consumed an average of 40 lpcd, P 36 lpcd, and VP 33 lpcd. After controlling for rural-urban development, seasons, and expenditures it was determined that non-poor households consume approximately 6 liters per person per day more than Poor or Very Poor households. To further disaggregate the socio-economic status into rural and urban areas respectively, the Non-poor (NP) households in urban areas use the most water, approximately 17 liters per person per day more when controlling for the effects of season, household size, and household expenditures[18]. Very Poor (VP) households in rural areas use the least amount of water, an average of 7.5 liters per person per day less than other households after controlling for other confounding variables.

3.5.2.2 Water Quality Monitoring

Water quality testing results were not included in this analysis but rather the frequency of water quality testing. In Burkina Faso this is based upon the: 1) service provider and 2) water source (refer back to Table 3-4). Tables G-1 and G-2 in Appendix G present the results of the

[18] Results of the models disaggregating water use by socio-economic status and rural and peri-urban are not shown.

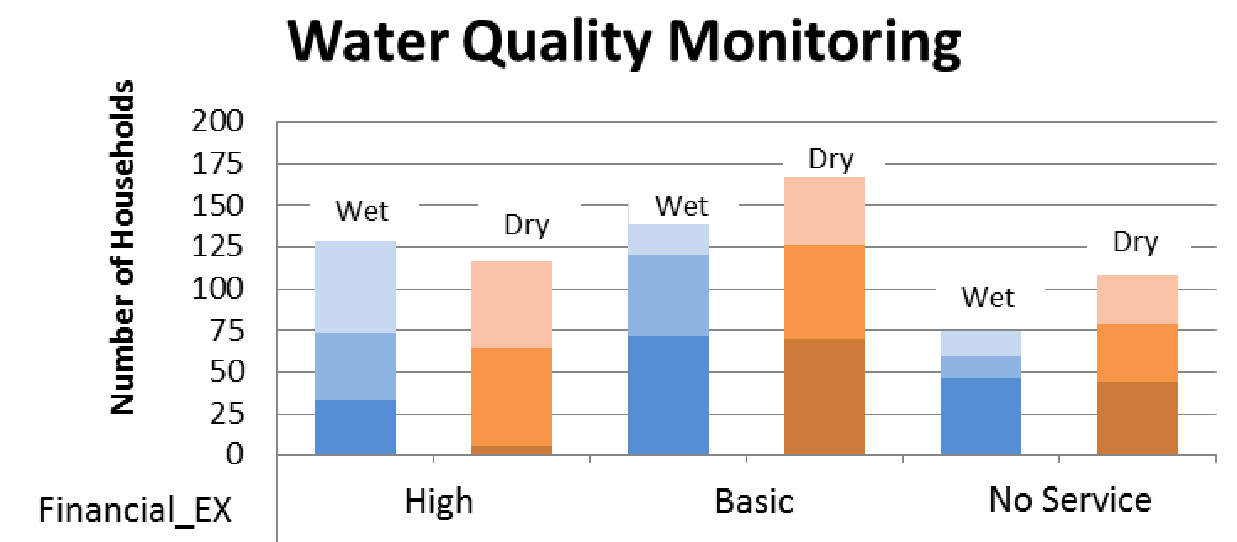
statistically significant parameters for water quality monitoring of the primary and secondary water points respectively. In the dry season, the primary water point for households had higher water quality monitoring scores (p=0.011). It is possible that this was due to the fact that greater availability of water during the wet season means that households use more informal sources. In addition, after controlling for household expenditures, rural households had less frequent water quality monitoring compared to urban households (p=0.000).

Households that invested more time in collecting water at their primary water point (i.e. collxn_time_wtpt1)[19] had less frequent water quality monitoring of that point, after controlling for rural-peri-urban effects (p=0.000). Also those households with higher financial expenditures had higher water quality monitoring indicator scores for their primary water point (p= 0.000). This suggests that perhaps water quality is not a driver of household time investment but rather water quality monitoring can be obtained through increased financial expenditures. Figure 3-4 explores this theory by comparing the water quality monitoring service levels and household investment tiers. Households are grouped into three categories T1-T3 based upon their expenditures. T1 is the highest 33 per cent, T2 the middle third, and T3 the bottom third. It is clear that most of those households that receive high service spend more money, a trend which is very apparent in the dry season.

For the water quality monitoring scores of the second preferred water point similar trends as the primary water point were observed with regard rural-urban differences and financial expenditures (model fit: ρ^2= 0.062). However, higher household opportunity costs (OPEXecon) were associated with better monitoring scores (p=0.000) and Non-poor (NP) households had

[19] Although collection time at the primary water point was significantly different amongst service levels, the economic expenditures (OPEXECON) were not. This is likely due to the difference in value of time between low levels of service (lower value of time and greater amount of time dedicated to water collection) and higher levels of service (higher value of time, but less time dedicated to water collection).

higher monitoring scores than Poor (P) and Very Poor (VP) households (p=0.002). See Table G-2 in Appendix G for the detailed results of this analysis.



Financial_EX	High (Wet)	High (Dry)	Basic (Wet)	Basic (Dry)	No Service (Wet)	No Service (Dry)
Highest (T1)	55	51	31	49	15	29
Middle (T2)	41	59	49	57	14	35
Lowest (T3)	33	6	72	70	46	44

Figure 3-4 Water quality monitoring service levels by season. Households are grouped into three categories based on their expenditures. T1 is the highest 33 per cent, T2 the middle third, and T3 the bottom third. Data was missing from 58 households in the dry season surveys. Sector 1 data excluded.

3.5.2.3 Accessibility

The accessibility indicator is composed of two criteria which were evaluated separately: 1) Distance from household to source and 2) Crowding at the source. The relationships between these indicators and the different independent variables observed were not very strong, resulting in models with low predicting power (R^2 and ρ^2 values were well below 1.0). The model describing the influence of expenditures and other factors on the distance to the source is show in Table 3-22. It is important to note that the model shown in Table 3-22 is for the distance travelled to the primary source and not the indicator score for Accessibility: Distance. For example a "higher" indicator score for distance (i.e. intermediate vs. basic) would mean a shorter distance travelled to the water source (refer back to Table 3-4 for the thresholds).

Seasonality and socio-economic status, as defined in this research (SES-2), did not have a statistically significant impact on the distance to primary source after controlling for the other variables and were hence excluded from the model. Rural households were located approximately 112 meters (β_3) further than urban households from their primary water source (p=0.004). Households with higher financial expenditures had closer primary sources (negative sign of β_1). An extra 1,000 CFA (US$2) per household per year in total financial expenditures (Financial_TOT) corresponds to a primary source that is approximately 1 meter closer.

Table 3-22 Effects of expenditures on the distance to water source. Units of the estimation coefficients (β values) are meters and the model fit is (R^2=0.213).

Dependent variable (units)	**Model parameters (p-values)**				
	Constant β_0	**Financial_TOT β_1**	**Cumm_TOT β_2**	**Rural β_3**	**Wtpt2_dist β_4**
Distance to primary source (meters)	93.912 (.014)*	-0.001 (.050)*	0.001 (.015)*	112.053 (.004)**	0.099 (.001)**

[1]Sector 1 data was not included in this model.
**. Relationship is significant at the 0.05 level (2-tailed), or 95 per cent significance
**. Relationship is significant at the 0.01 level (2-tailed), or 99 per cent significance.

The relationships for crowding were less strong than those for the distance. There was a weak fit for models for both the primary source (ρ^2=0.021) and secondary source (ρ^2=0.056) Tables G-3 and G-4 in Appendix G provides details of this analyses for the primary and secondary water points respectively. Excluding Sector 1 data and controlling for socio-economic status, expenditures, rural-urban development, season, and other factors, crowding at the primary (p= 0.015) and secondary (p=0.016) water points was less for households that had higher economic expenditures. Crowding was less at the secondary source for households that had higher financial expenditures (p=0.009).

The difference between socio-economic status (SES-2) was not found to be significant for the crowding at the primary water source (see Table G-3 in Appendix G). However, when evaluating the crowding at the secondary water source, Non-poor had less crowing than the Very Poor (VP) and Poor (P) households p=0.003). More crowding occurred when households increased the volume of water collected at their primary water point (p=0.047). Crowding scores at the second water point increased during the dry season (p=0.000), however no statistically significant seasonal affect was seen in crowding at the primary water point.

3.6 Conclusions

The objectives of the research presented in this chapter were to determine how household expenditure - financial, economic, and cummulative - in formal water sources vary across socio-economic status categories in the study areas and evaluate the influence of these expenditures on the water service levels received by households. In addition, the analyses uncovered the impacts of season, rural-urban differences, and other influences on spending behavior.

3.6.1 Per-person Expenditures

- Capital expenditures (CAPEX) were approximately US$ 1.5 per person and only one third of households reported making a CAPEX contribution.
- Capital maintenance expenditures were US$2 per person per year; most of these expenditures were for the purchase of transportation and storage containers.

- Financial operating expenditures estimated from yearly expenditures (OPEX1) or from daily water collection (OPEX2) were similar and ranged from US$7.5 in the wet season to US$9.5 per person per year in the dry season.
- Using the annual reported household income to determine the value of time for collecting water, the average economic expenditures ranged from US$5 in the wet season to US$9 per person per year in the dry season.
- Assuming 4 wet season months and 8 dry season months, the average annual per person cumulative costs were approximately US$19.5.
- Households that use a handpump as their primary source spend an average of $58 per person per year on that source. This is significantly greater than the US$0.50 (250 CFA) per person per year affordability target that the Burkina Government uses for households accessing a borehole.
- Households using standpipes spend $15 per person per year on that source and private connections spend approximately $23.5 per person per year.

3.6.2 Household Expenditures

- No statistically significant difference in absolute household financial expenditures in water was observed between the socio-economic categories in the study, however differences in relative household spending were observed.
- Comparing financial expenditures on water to total household expense VP spend 8.3 percent more than NP and P households (p=0.016).
- The average total financial expenditures in water as a per cent of household income for all socio-economic categories in this research (25 per cent) was well above the

affordability threshold of 5 percent which is used by World Bank and others (Banerjee and Morella 2011).

- Comparing only the financial operating expenditures on water ($OPEX_{FIN}$) to household income or to total household expenses, the values (17 and 12 per percent respectively) is still well above the affordability threshold.
- Very Poor households spend $23 per household per year less than Poor and Non-poor households in economic terms. This is primarily due to a lower value of time: VP 16.5 CFA per hour, P= 23 CFA per hour, NP = 34.7 CFA per hour. Poor and Very poor households dedicate more time to water collection at their secondary and tertiary water points.
- Rural households pay approximately US$17 per year less than urban households for their water, but dedicate approximately 80 minutes more per household per day in collecting their water. Despite dedicating more time to water collection there is no statistically significant difference in economic expenditures between rural and peri-urban households.
- In the dry season, households have higher financial and economic expenditures as compared to the wet season. Financial expenditures in the dry season can be US$1.5 per household per month greater, while economic expenditures can be US$2 per household per month more.

3.6.3 Service Levels

- The price of water in the communities in the study varied significantly as shown in Table 3-23.

Table 3-23 Price (US$) per cubic meter of water in study communities. Data is from the primary water source.

Primary Water Source Technology	Rural	Peri-urban		
		Sector 2	Sector 30	Sector 1
Private Connection	$1.43	$0.12	$0.77	$0.97
Standpipe	$1.07	$0.54	$0.98	$0.75
Handpump	$0.36	$0.10	N/A	$0.11

- The prices reported in Table 3-23 are within the range of prices observed in a study from (Ougadougou, Burkina Faso): standpipe - US$0.59/$m^3$, household connection US$1.11/$m^3$, water vendor US$2.05/m^3 (Keener et al. 2009[20]).
- However the marginal cost of an additional unit of water is significantly higher. Controlling for confounding factors (SES, season, and rural-peri-urban effects) households had to spend an additional 1000 CFA (US$2) per year per person to receive an extra liter of water per person per day, putting the implied marginal financial cost of a cubic meter of water (1,000 liters) at 2,740 CFA (US$5.45).
- Non-poor households consume approximately 6 liters per person more than Poor or Very Poor households. Non-Poor households consumed an average of 40 lpcd, Poor: 36 lpcd, and Very Poor: 33 lpcd
- Urban households and households that had higher financial expenditures had higher water quality monitoring scores.
- The distance to each household's primary source did not vary significantly by season or socio-economic status. In general, rural households were further from their sources (112 meters further) and households that had greater access with regard to distance paid more for their service.

[20] Values adjusted for inflation.

- Households that had higher per person financial expenditures had less crowding at their primary and secondary water sources and those with higher economic expenditures has less crowding at their secondary water source
- Socio-economic status did not impact crowding at the primary water point; however the Very Poor and Poor (P) households had greater crowding than the Non-poor households at their secondary source.
- Although crowding scores were better in the dry season, this is likely due to a large percentage of households that use informal sources during the wet season.
- Overall service levels were greater for the Non-poor and those with greater per person financial expenditures.
- Households with higher economic expenditures per person per year had better indicator scores for: water quantity as well as water quality monitoring and crowding at the secondary water point. There was no statistically significant relationship between economic expenditures and overall service level or the distance to or crowding at the primary water point.

3.7 Policy Implications

In a review of Africa's Water and Sanitation infrastructure, Banerjee and Morella (2011) determined that on average Africa households spend US$4 per month on water, or approximately 2 per cent of household income. They cited indicative tariff ranges of US$2-8 per household per month for consumption between 25 and 60 lpcd, with the upper range representing CAPEX recovery tariffs. Considering the average expenditures and household size observed in household surveys in Burkina Faso (see Tables 3-5 and 3-9) the range of monthly expenditures for the average household is between US$6-$8.5. Banerjee and Morella looked primarily at urban areas and used GDP per capita as the metric for determining affordability to households. They concluded that approximately 60 per cent of African population can NOT afford to pay cost recovery tariffs, which appears to be the case in many of the households in this study in Burkina Faso where the financial investments represented a significantly greater percentage of reported income. Considering the lower service levels received by poor and very poor households and the greater relative contribution to these services, affordability and equity become paramount and there is an added human rights dimension to the situation.

Research has demonstrated that most water subsidy mechanisms in Africa are poorly targeted and fail to reach the poor, in part, because the poor lack access to water networks which operate under the subsidies (Banarjee and Morella 2011). The indicator used to measure how effectively a subsidy is at targeting the poor is: the percentage of the total subsidy received by the poor divided by the percentage of the population that is poor (Komives et al. 2005). In 2008, Burkina Faso had the second lowest targeting performance indicator (Ω) score out of 19 Sub-Sahara African (SSA) countries. Burkina Faso had connection rates amongst the poor (compared to the total population) that were lower than in any other SSA country except for Rwanda (Banarjee et al. 2008). In Burkina Faso the existing water subsidies are not targeted to any specific customer income category and there are questions as to whether the connection costs, followed by monthly bills, is within the means of low-income households.

One way to reach the poor is to provide a subsidy to those households which are not connected to the network. If Burkina Faso were to adopt this scenario estimates suggest that (Ω) would increase from 0.02 to over 1.0, meaning that the poor would receive a higher percentage of the overall subsidy distributed relative to their percentage of the overall population (Banarjee et al. 2008).

Although financial sustainability of many of the water systems in operation in Burkina Faso is questionable (Pezon et al. 2012), based upon the relative household expenditures determined in this research, requesting greater contributions from households does not seem appropriate. Innovative subsidy mechanisms need to be developed in order to ensure that the subsidy benefits are delivered to the most vulnerable populations as designed. Although the National Office for Water and Sanitation (ONEA) has made great strides to extend water services to informal settlements in Ouagadougou, current increasing block tariffs subsidize subsistence consumption and household connections but water poverty maps produced by the University of Ouagadougou suggest that these efforts exhibit only "patchy" inclusion of the poor. ONEA can improve subsidy targets by utilizing poverty mapping (i.e. geographic targeting) or other methods such as proxy (e.g. household characteristics), income-based, community-based, or even self-targeting (Newborne et al. 2012). It is important that "pro-poor" obligations are included in performance contracts between service providers and service authorities.

A pro-poor policy in rural area is more complex to achieve because of the prevalence of alternative water sources. Even in the dry season, when formal sources are most utilized, one third or more of households still utilize informal sources to satisfy some portion of their domestic needs. Rural households are particularly vulnerable to non-functionality of water points in dry season, with secondary water points being 60% more distant than in the rainy season. In the rainy season 10% of rural households use informal sources as their primary water point. The quality of unprotected water sources (i.e. informal or traditional sources) poses a significant health risk to the populations utilizing water for drinking, cooking and bathing. The benefits of rural water supply infrastructure projects may not be fully realized if households switch between formal and informal sources and do not distinguish between uses. Informal and formal water points complement each other, depending on seasons, crowding and affordability. A pro-poor policy would prioritize a high functionality rate of formal sources in the dry season (to the benefit of all poverty categories) and in addition, provide strategic support (e.g. point-of-use treatment options) so that households may continue to utilize informal sources. These forms of self-supply are ways that households cope with over-crowded, distant, or expensive formal water points.

This research supports the inclusion of affordability and equity indicators into the framework for measuring access, to not only water services but to all WASH services. Affordability of WASH services is an important barrier to access and must be considered in future Joint Monitoring Programme (JMP) monitoring frameworks. Furthermore, if the elusive goal of universal WASH coverage is to be achieved, it is important to address the economic contexts which often lead to low service sustainability and low utilization. Economic development and WASH development are integrally related and as universal coverage is considered it is critical to identify economic factors that might result in slippage over the long term (e.g. weak private sector capacity).

4 WATER TREATMENT: FIELD ASSESSMENT OF CERAMIC WATER FILTERS

4.1 Background

Household water treatment technologies can be divided based on the category of the principal mechanism that they implore: thermal, chemical, or physical (Fry et al. 2013). The range of potential mechanisms (or subcategories) are listed Table 4-1. It is important to note that any given treatment technology can utilize a number of different specific mechanisms. Subcategories of the mechanism of physical removal include: sedimentation, aeration, and filtration. This chapter will focus on filtration. There are many different media used in filtration, including fiber, fabric, granular, membrane, and porous ceramic, however, this chapter is focused on porous ceramic as a filtration media.

Table 4-1 Three principal mechanisms used in household water treatment technologies (along with the subcategories) (Fry et al. 2013).

Thermal	Chemical	Physical
Boiling	Coagulation and flocculation	Sedimentation
Pasteurization	Disinfection	Aeration
Ultraviolet irradiation		Filtration

4.1.1 Porous Ceramic Filters

As particles and contaminants pass through the porous ceramic microstructure they are physically trapped through various transport mechanisms. Different transport mechanisms that lead to particle removal in a porous ceramic structure are described in Table 4-2.

Table 4-2 Transport mechanisms in physical removal(Crittenden et al. 2005)

Removal Mechanism	Description
Straining	Sieving action
Interception	Particle collision with bed grains due to streamline proximity
Diffusion	Passive transport due to random Brownian motion
Sedimentation	Gravitational forces that cause settling inside quiescent boundaries
Hydrodynamic	Rotational motion due to velocity gradients

In addition to these transport mechanisms, there are attachment mechanisms that are governed by physio- and electro-chemical forces that occur at the molecular level. These attachment mechanisms are described in Table 4-3. Macroporous[21] ceramic filters were shown by van Halem (2006) to remove particles significantly smaller than their average pore size suggesting removal via other mechanisms besides simple size exclusion (i.e. straining).

Table 4-3 Attachment mechanisms in physical and chemical removal(Crittenden et al. 2005)

Removal Mechanism	Description
Coagulation	Colloidal destabilization to encourage particle growth/flocculation
Adsorption	Mass transfer from gas to solid or liquid to solid phase
Ion exchange	Demineralization driven by electro kinetic forces

Porous ceramic water filters have many different functional designs, ceramic material types, and geometric shapes. Designs range from complicated pressurized systems to simple gravity and siphon set ups. Complex systems requiring electricity, pumps, and technical expertise for installation, operation, and maintenance have limited applicability in resource poor settings. As a result simplistic ceramic technologies are more common in developing countries.

The necessary materials to make porous ceramic are widely available and the basic knowledge has existed since at least the Gravettian culture of 25,000-28,000 B.C.E (Vandiver 1990). Materials used to manufacture porous ceramic filters include: clay, water, and a

[21] Van Halem found average pore size of ceramic filters to be 40 µm (range of 33-52 µm) which corresponds to Crittenden et al. (2005) definition as macroporous.

combustible material such as saw dust or rice hulls. This combustible material is added to increase porosity of the fired ceramic and enhance flow rate of water through the microstructure. There is a large variety of clay material properties (type, particle size/distribution, plasticity, purity, shrinkage behavior, moisture content, grain strength, particle bond strength, etc.) as well as a similar variability in combustible materials (type, size, shape, percent organics, etc.). As a result there is a wide range of material characteristics of the finished (fired) porous ceramic. Detailed discussion of these variables as well as mix ratios and other production variables and their impact on filter performance is available elsewhere (Lantagne et al. 2010; Raynor 2010; van Halem 2006). This makes ceramic water filters viable for local production in resource poor settings.

Due to the plasticity and versatility of unfired clay, filters can assume a wide variety of shapes, most common are: discs, cylinders (i.e. “candles”), frustum (i.e. “pots”) or paraboloid. Candle and disc filters are often made from synthetic ceramic. As noted elsewhere (Oyanadel-Craver and Smith 2008), this requires high-purity raw materials and an industrial manufacturing processes, often resulting in a more expensive final product. Therefore this research will focus on the frustum and paraboloid-shaped ceramic water filters. For the remainder of this report ceramic water filters (CWF) will signify locally produced porous ceramic filters of the frustum or paraboloid shape.

4.1.2 Locally Produced Ceramic Water Filters (CWF)

CWF are currently manufactured in at least 20 countries (See Figure 4-1). Over thirty-five manufacturing facilities produce between forty-five and 4,480 filters per month, averaging 1,500 filters per month (Raynor 2010). Ceramists, development practitioners, scientists, engineers, academics, and others are involved in research and design development of the CWFs. The Ceramics Manufacturing Working Group has recently emerged with the objective of identifying, researching, and refining the best practices in the manufacturing of CWFs. An incremental improvement in CWF technology came with the addition of silver to enhance the treatment efficiency. Laboratory research has demonstrated the role of silver in the removal of microbial contaminants (Bielfeldt et al. 2009; Albert et al. 2010; Lantagne et al. 2010). Further discussion of the role of silver in ceramic water filters can be found in Appendix H. A schematic of the basic CWF is shown in Figure 4-2.

Figure 4-1 Countries with ceramic water filter factories. Twenty countries have over thirty-five factories in total that produce between 45 filters and 4,480 filters per month, averaging 1,500 filters per month (n=25). Source: Raynor (2010). Map generated using www.traveltip.org.

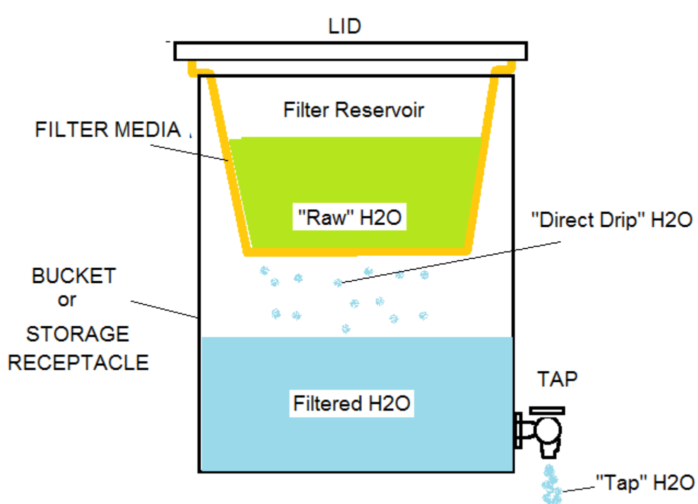


Figure 4-2 Schematic of ceramic water filter

4.2 Research Objectives

The research outlined in this chapter seeks to evaluate, in the field (as well as the laboratory), the long term performance of two different filter designs imploring different silver application methods. This research compliments previous research conducted on similar filter designs, however, that research was only performed in the laboratory (Lantagne et al. 2010). One of the important deficits in knowledge regarding household water treatment technologies in general, and ceramic water filters specifically, is the long-term field performance. Many studies have evaluated individual filter function after years in service (Roberts 2003; Brown et al. 2007; Westphal 2008;) while others have followed filter performace over a few months period (AFA/Guatemala 1996; Ay-Moyed 2008; Dundon 2009); however, monitoring over a long period is limited. In fact, only one study has monitored field performance for a period over one year (Kallman et al. 2011). Therefore the objectives of this research are to:

- Conduct a long term-term continous (longitudinal) study that monitors hydraulic operation (efficiency) and water quality performance (effectiveness).
- Characterize filter user opinions and document usage behaviors over the study period of 14 months.
- Identify factors affecting filter field performance

A review of the literature suggests that microbial removal performance in the field is significantly lower than laboratory performance. In addition, many researchers have suggested that this difference can be attributed to deficiencies in household hygiene and use (Lantagne 2001b; Roberts 2004; Kallman et al. 2011). Accordingly, the hypothesis for this resarch is that improper quality control and variable filter performance is as significant as or more significant than the user related issues. We also believe that cross-sectional studies have been overly optomistic about the performance of the filters and we believe that continuous studies will identify the issues of user acceptance and the obstacles to scaling up filter use. The next section discusses the existing research on CWF.

Table 4-4 Cited literature on ceramic water filters. Only frustum-shaped or paraboloid-shaped ceramic water filters are considered. This table excludes all research on other forms of ceramic water filters (e.g. disc or candle filter). Although there may be important lessons learned from this research, the technologies vary greatly in production, materials, and most importantly user issues (e.g. operation and maintenance).

Laboratory Studies		Field Studies	
Baumgartner et al.(2007)[*]	Lantagne (2010)[*]	AFA (1996)	Johnson (2008)[†]
Bielfeldt et al. (2009)[*]	Larimar (2010)[*]	Al-Moyed (2008)	Kallman et al. (2011)[*]
Bielfeldt et al. (2010)[*]	Lee (2001)	Archer et al. (2011)[*]	Kleiman (2011)
Bielfeldt (2003)	Mattelet (2006)	Baide (2001)	Lantagne (2001b)
Bloem (2009)	Miller (2010)	Brown et al. (2007)[*]	Lemons (2009)
Brown (2009)	Napotnik (2009)	Brown et al. (2008)[*]	Narkiewicz (2010)
Brown et al. (2007)[*]	Oyanadel-Craver & Smith (2008)[*]	Brown et al. (2009)[*]	Nims (2000)
Brown & Sobsey (2010)[*]		Bullard (2002)[**]	Partners for Development (2002)
Cambell (2005)	Schweitzer et al. 2013	Cadena (2003)[**]	
Duke (2009)	Simonis & Basson (2011)[*]	Cassanova (2011)[‡]	Plappally et al. (2011)[*]
Duke (2009)	Stewart (2010)	Clopek (2009)	Roberts (2004)[†]
Estrada (2001)[**]	Tun (2009)[*]	Desmeyter et al. (2009)[†]	Smith L. (2004)[**]
Eriksen (2002)	van Halem (2006)	Dochary (2004)	Smith J. (2011)[‡]
Fahlin (2003)	van Halem (2009)[*]	Dundon (2009)	Swanton (2008)
Klarman (2009)	Vidal Henao (2010)	Green (2008)	Valerio (2001)[**]
Kohler (2009)	Watters (2010)	Hwang (2002)	Walsh (2000)
Lantagne (2001a)	Westphal (2006)[**]	ICAITTI (1994)	

***Articles published in peer-reviewed journals.**
****Works could not be obtained as they are only available in hardcopy and are non-circulating.**
† Manuscripts published in peer-reviewed conference proceedings.
‡ Research presented at a conference, but no associated proceedings or publications.

4.3 Literature

There has been a large quantity of research on CWF; however, a significant amount has remained unpublished (See Table 4-4). Within this gray literature there are at least 6 studies that are referenced but no documents could be obtained (e.g. non circulating masters theses or unpublished internal documents available only in hardcopy). Two thirds of the publications from peer reviewed journals are on research from controlled laboratory settings on a small sample of

CWFs. Detailed laboratory studies can describe how a product or technology will perform in a very specific environment, however, the conditions of use of filters in the field during their lifespan can potentially be more severe and varied. This is the fundamental justification for conducting field testing of any consumer product.

4.3.1 Microbial Water Quality – Treatment Effectiveness

Microbial water quality is commonly determined using specific tests that identify the presence of indicator bacteria. These indicator bacteria are correlated with the presence of other disease causing organisms, although the indicator bacteria do not necessarily cause disease themselves. The most commonly used indicator organisms are: total coliform bacteria, thermo-tolerant bacteria, Escherichia coli (E. coli), and hydrogen sulfide producing bacteria. More information on the specific indicator organisms and test methods used in this study can be found in Appendix I.

Table 4-5 World Health Organization risk classification scheme. This scheme is used for establishing targets for improvements of water supplies. Table is adapted from the World Health Organizations Guidelines for Drinking Water Quality 4th Edition (WHO 2011). CFU refers to coliform forming units.

	Sanitary inspection risk score			
Escherichia coli: CFU* per 100mL	***0-2***	***3-5***	***6-8***	***9-10***
<1	Low	Intermediate	High	Very high
1-10	Intermediate	Intermediate	High	Very high
11-100	High	High	High	Very high
>100	Very high	Very high	Very High	Very high

*-Sanitary inspection scores indicate susceptibility of the water supply to contamination from human and animal feces. WHO provides example sanitary inspection forms that can be used to determine sanitary risk scores associated with various water supplies in Davison et al. (2005).

The World Health Organization (WHO) guidelines suggest that drinking water should have no fecal coliforms measured indirectly by the presence of E. coli in any 100 mL sample of water. Many household and small community drinking water systems in both developed and developing countries may fail to meet this guideline for microbial quality. As a result WHO has developed a risk classification scheme to establish realistic targets for the progressive improvement of water supplies (WHO 2011). This classification scheme utilizes both qualitative and quantitative grading since water testing is often conducted infrequently and dependence on statistical analysis may be inappropriate (WHO 2011). The sanitary inspection scoring is based upon a list of diagnostic questions (10-12) evaluating the status of different water supply facilities (Davison et al. 2005). It is then compared to the results of water quality data facilitating the identification of the most probable causes of contamination and the appropriate control measures for mitigating this risk. A summary of this scheme is provided in Table 4-5. It is important to note that under this risk classification scheme no category exists for "No risk" so therefore even samples that meet the WHO guidelines for microbial contaminants (i.e. 0 CFU E. coli per 100mL sample) will be at a "low risk." Therefore in the subsequent tables when values are presented as "meets guideline" and "low risk," the former is included in the latter category (See Table 4-6 and 4-7 for examples).

Table 4-6 The results of cross-sectional field studies of ceramic water filters.

Reference	Location	Households	Filter Age (months)	WHO Criteria: Meet Guideline (# samples)	WHO Criteria: Low to Intermediate Risk Categories (# samples)
Partners for Development (2002)	Cambodia	135	NR	59% (n=135)	95% (n=135)
Roberts (2003)	Cambodia	686	4	81% (n=686)	99% (n=686)
Brown et al. (2007)	Cambodia	80	0-48	40% (n=211)	66% (n=211)
Johnson (2007)	Ghana	25	0- 12	69% (n=26)	92% (n=26)
ICAITTI (1994)	Guatemala	302	0-12	93% (n=302)	NR
Lantagne (2001b)	Nicaragua	24	6-18	29% (n=7)	NR
Westphal (2008)	Nicaragua	43	12-48	53% (n=43)	NR
	Average	**185**	**N/A**	**75% (n=1,410)**	**92% (n=1,058)**

NR-not reported

Of the thirty-two field studies listed in Table 4-4 only thirteen quantified the presence of E. coli in the filtered water and reported the total number of filtered samples with E. coli present. These studies are presented below and segregated into cross-sectional studies (Tables 4-6) and longitudinal studies (Table 4-7). It is important to note that none of the studies reported sanitary inspection scores, so the risk categorization presented represents the most optimistic case. In other words it is assumed that if the sanitary inspection risk score is 0-2 and therefore less than 1 CFU per 100mL that would be Low risk, 1 to 10 would be Intermediate risk, etc.

Table 4-7 The results of longitudinal field studies of ceramic water filters.

Reference	**Location.**	**households**	**Duration (weeks)**	**Visits to households**	**WHO Criteria**	
					Meet Guideline (samples)	**Low to Intermediate Risk Categories (samples)**
Brown et al. (2008)	Cambodia	60	18	9	40% (n=604)	59% (n=604)
AFA/Guatemala (1996)	Guatemala	343	52	3	91% (n=NR)	NR
Kallman et al. (2011)	Guatemala	62	52/ 92	10	71% (n=417)	96% (n=417)
Hwang (2002)	Nicaragua	100	24	6	71% (n=49)	94% (n=49)
Dundon (2009)	Peru	58	12	3	69% (n=71)	83% (n=71)
Al Moyed (2008)	Yemen	20	24	3	95% (n=20)	NR
	Average	**107**	**26**	**5.7**	**55% (n=1,161)***	**76% (n=1,141)**

NR-not reported

Just as laboratory studies may oversimplify the challenges that CWF will inevitably face during usage in the field, the weakness of cross-sectional studies is that the variability of raw water characteristics cannot be reflected. Narkiewicz (2010) observed a ten-fold fluctuation in raw water quality (6,000 CFU/100mL to 56,000 CFU/100mL) for field measurements made in South Africa during the rainy season. Therefore in order to accurately gauge the performance of a POU treatment technology from a user's perspective it is necessary to track filter performance in-situ and over time. The results of the longitudinal field studies performed on ceramic water filters are shown in Table 4-7.

Tables 4-6 and 4-7 show there is a significant difference in the percent of samples meeting WHO standards or the Low to Intermediate Risk categories between the longitudinal studies (55% and 76%) and the one time cross-sectional studies (75% and 92%). This is despite a similar sample size and the fact that there is overlap between the longitudinal and cross sectional studies with some conducted in the same countries (3) or even the same community (1). Field studies have been conducted using other indicator organisms such as total coliform (Swanton 2008) or hydrogen sulfide producing bacteria (Walsh 2000; Donarchy 2004) although no risk classification scheme exists as these indicator organisms are not as widely used as E. coli. In addition, there are studies that collected data on E. coli removal but presented the data in another format such as percent removal or log removal; however, these are not presented here.

4.3.2 Filter Maintenance and Recontamination

In an effort to explain the discrepancy between laboratory performance and field performance researchers have suggested a number of potential reasons. The most commonly cited reasons for the decreased performance in the field are improper filter use and/or improper or inadequate filter maintenance. Walsh (2000) found that 68% of households (n=130) were running chlorinated water through their filters which can accelerate the silver leaching process and reduce the efficacy of the filter. 27% were using soap when cleaning the ceramic membrane which can also interfere with the proper function of the filter (Walsh, 2000).

Table 4-8 Field studies of locally produced ceramic water filters. Shown are values of the percent of filtered water samples with higher concentration of E. coli and total coliforms as compared to raw water samples.

Reference	Location	Percent samples with higher microbial contamination in filtered water
Brown et al. (2007)	Cambodia	50% (n=79)
Brown et al. (2008)	Cambodia	5% (n=NR)
Johnson (2007)	Ghana	19% (n=26)
Clopek (2009)	Ghana	24% (n=72)
Kallman et al. (2011)	Guatemala	17% (n=417, E. coli) 8% (n=468, TC)
Lantagne (2001b)	Nicaragua	56% (n=15, E. coli) 100% (n=15, TC)
Hwang (2002)	Nicaragua	13% (n=48, E. coli) 7% (n=44, TC)
Narkiewicz (2010)	South Africa	0% (n=30)
	Average*	**23% (n=687)**

*** If both E. coli and Total Coliform values were reported the higher value was used.**
TC= Total coliform NR=Not reported

Field studies have not only demonstrated decreased microbial performance as compared to laboratory studies, but they also have documented NEGATIVE removal or filtered water samples with higher bacterial concentrations than measured in the untreated water. For example, Brown and colleagues (2007) observed up to a 3 log increase in E. coli in some filters in the field. Table 4-8 shows the results of these studies.

Many studies characterize higher contaminant levels in filtered water as "recontamination" which suggests that the raw water is improved by the filter and then contaminants are reintroduced. The plastic bucket (see Figure 4-2) is designed to protect the filtered water from recontamination by human hands or other devices used to extract the water (cups, ladles, etc.). However, Sobsey et al. 2006 stated that "it is commonly observed that post-filtration contamination of water occurs during storage due to bacterial growth" (pg-24). Sobsey and colleagues did not quantify growth inside storage containers nor was any correlation shown between reported frequency of use, frequency of cleaning, method of cleaning the filter or bucket or other user related factors that may influence "recontamination" (Sobsey et al. 2006). AFA Guatemala (1996) was the first to hypothesize that the hygiene of the storage unit contributed to the "recontamination" of filtered water. Since then at least ten of the 31 field studies reported the need to improve training and hygiene education in the use of CWF to reduce recontamination risk. Although it is prudent to ensure that users are aware of the proper hygiene and maintenance procedures it is unclear if there is a greater risk of user "recontamination" or of suboptimal filter performance.

In studies as many as 60-78% of households were observed cleaning their filters with untreated source water that was potentially contaminated (Lantagne 2001b; Swanton 2008; Kallman et al. 2011). However, the relationship between low quality filtered water and the water used to clean the filter, as well as other hygiene factors (e.g. household cleanliness, private latrines) is anecdotal and not statistical (Lantagne 2001b; Roberts 2004; Kallman et al. 2011). Studies have cited other potential sources of recontamination including infrequent cleaning (Bullard 2002). In contrast, others warned that excessive cleaning may lead to higher breakage rates and may actually contribute to recontamination (Roberts 2004; Kallman et al. 2010). Multi-use washcloths that are used to clean filters have also been identified as an important vector for germs (Sobsey et al. 2006). Another risk is overfilling the filter which can cause raw water to flow directly into the storage receptacle (Hwang 2002; Swanton 2008). Baumgartner and colleagues (2007) observed a significant difference between filtrate waters for filters that were operated normally and those that were overfilled. E. coli removal decreased from 99.8% to 48.7% for those filters which were overfilled (Baumgartner et al. 2007). Some suggest that the plastic storage container itself may be less than ideal to maintain the integrity of filtered water

(Lantagne 2001b), especially if there are insufficient levels of silver in filtered water to prevent microbial growth (Narkiewicz 2010).

However, to the author's knowledge all in-situ studies collected "filtered water" samples directly from the tap on the side of the bucket (see Figure 4-2). Therefore for the case of low or negative removal it is difficult to determine if the filter functioned properly and the water was subsequently re-contaminated or if the filter simply did not work. Recent laboratory research observed bacterial contamination of clean water passing through the CWF, a result of desorption of pathogens from within the pores of the ceramic (Bielfeldt et al. 2010). This is just one potential source of "recontamination" that is not due to user behavior, and therefore seriously calls into question the scalability of CWF at this time.

Apart from recontamination (whether from the user or from other sources) there are other possible reasons for the difference between laboratory studies and field studies including: selective reporting, bias in selection of sample sites, and procedural variables (e.g. longer sample holding times, challenges due to infrastructural deficiencies). However, a detailed analysis of these factors is beyond the scope of this dissertation.

4.3.3 Hydraulic Efficiency

It is critical that any POU treatment technology provide sufficient water to meet the demands of the household. Howard and Bartram (2003) determined that a minimum of 3 liters/person/day is required to meet basic drinking water needs. However, when factoring in other needs (e.g. food preparation, demand of lactating women, and rehydration demands from manual labor) 7.5 liters/person/day is a more appropriate estimate (Howard, 2002).

Technologies that do not meet these requirements or more importantly the expectations of the users have little practical value (Lantagne, 2001b).

In a survey used to develop a Best Practices Manual for CWF production, Raynor (2009) reported that all filter factories who participated (n=20) reported using flow rate as a quality control metric. Eighteen factories test 100% of their filters and the other two test 8% and 4% respectively (Raynor 2009). Each factory has an established acceptable flow rate range used for quality control which ranges from 1.0-3.0 liters/hour minimum to 2.0-5.0 liters/hour maximum (Raynor 2009). These manufacturer-reported ranges corroborate with previous observations of filter factories made by researchers (Lantagne 2001b; Mattelet 2006; Johnson 2007; Kallman et al. 2011).

The lower value in the range is based on the average water demand of filter users. The most common value used (1.0 liter/hour) was initially established considering the average material porosity (40%), an ideal silver contact time (20 minutes), and a minimum water requirement per household (5 liters/person/day). To ensure sufficient contact time with colloidal silver and also maintain adequate mechanical screening, 1 μm was determined as an optimal pore size (van Halem 2006). Although this flow rate is the most common minimum acceptable flow rate used for quality control testing, it has been determined that a higher rate is necessary. The "initial" flow rate represents the best case scenario (i.e. the full filter flow rate is the fastest flow rate) and therefore van Halem (2009) recommended 2.0 liters/hour as an alternative minimum.

The upper bound of quality control is used to prevent distributing filters with cracks or imperfections. Filtration rates above 2, 2.5, or 3 liters/hour (commonly cited values) could indicate imperfections in the ceramic which might compromise performance (Lantagne 2001b; Kallman et al. 2011). More recently Lantagne et al. (2010) evaluated 36 filters in the lab and found that flow rates above 1.7 liters/hour led to percent removal less than 99% and thus established this as the maximum acceptable flow rate that should be used by manufacturers during quality control. However, Bloem et al. (2009) reported contradictory findings from their laboratory study on 14 filters which showed that flow rate could be increased up to 7.0 liters/hour without compromising effluent quality. Finally Kallman et al. 2011 conducted laboratory trials on cylindrical ceramic media produced in the lab and found that increased porosity (and hence flow rate) accounts for higher uptake of silver and increased microbial removal efficiency. Kallman and colleagues (2011) recommended maximizing the flow rate by increasing the ratio of combustible material to clay ratio (i.e. burnout ratio) taking into consideration the increased fragility of filters with a high burnable ratio. The lack of consensus on the target range for flow rate testing suggests that hydraulic efficiency should not be used as a quality control measure.

Only five of twenty-seven (reviewed) studies conducted on locally produced CWFs monitored and reported in-situ flow rate measurements. In these studies although 50-85% of respondents reported the volume of water to be sufficient, based upon the reported family size and filtration rates it is questionable that the water produced is sufficient to meet their basic needs (See Appendix J). Although a higher filtration rate is achieved by maximize head within filter (e.g. constantly re-filling filter), this can be inconvenient and reduces user acceptance (Hwang 2002).

4.3.4 User Acceptance

Sustained use of the filter is the most important metric of user acceptance. The most comprehensive study of filter sustained use was a cross-sectional study conducted in 13 rural villages in Cambodia (Brown et al. 2009). In each household (n=506) "use" was defined as meeting the following criteria: 1) having a filter in good working order that 2) contained water or was damp from recent use with 3) one or more household member reporting the daily use of the filter for producing drinking water (Brown et al. 2009). Only 31% (n=156) were using the filter regularly at the time of the visits. Use was strongly associated with filter age, determined by the serial number stamped on the ceramic by the manufacturer. Usage decreased by 2% per month with the most common reason for disuse (65% of n=350 not using) breakage of ceramic or tap, followed by slow filtration rate (5%), and finally the user perception that it was no longer effective (5%) (Brown et al. 2009). Controlling for time, the other factors tied to usage include: water source and perceived quality, access to sanitation, the practice of other specific hygiene behaviors in the household, and investment in the filter (Brown et al. 2009).

Cash investment, at any level, by the household in the filter was associated with continued use versus receiving the filter free of charge. Of the people not using the filters 72% (n=251) were given filters, while for the people using the filters 72% (n=112) purchased them (Brown et al. 2009). This trend is reflected in other research (Valerio 1999; Valerio 2000; Roberts 2004; Clopek 2009). Appendix K provides a table of the disuse rates and household investments for different CWF field studies. In addition to the Cambodia study, others have observed similar factors affecting the willingness by households to invest in WASH technologies. Prokopy (2002) found that poor water quality motivated individuals to contribute to WASH interventions. Biscoe et al. (1981) showed households were willing to travel greater distances to find better quality water.

4.4 Filter Designs

In the Dominican Republic there are two different manufacturers making ceramic water filters. A Dominican non-profit organization, Instituto de Desarrollo de la Economía Asociativa (IDEAC) developed a partnership with a local ceramics artisan group. As a part of the rehabilitation effort following Hurricane Georges in 1998, IDEAC and the artisan group were trained by representatives from Potters for Peace in the manufacturing of frustum-shaped CWF. Intermon Oxfam and a Spanish savings and loan bank (Caja de Ahorros Mediterraneo) provided financing to establish a filter factory in Yamasa where the artisan group is based. The filter produced by the artisan group and IDEAC is shown in Figure 4-3b.

a) Paraboloid b) Frustum

Figure 4-3 Two ceramic water filter designs produced in the Dominican Republic. a) FilterPure paraboloid design b) Frustum design by Potters for Peace which is manufactured by an association of ceramics artists in coordination with a Dominican non-profit, IDEAC.

The second organization with CWF manufacturing operations in the Dominican Republic is the non-profit AguaPure, founded in 2006. AguaPure is a franchise of the US based non-profit organization FilterPure. Their paraboloid design implores a round bottom to reduce risk of contamination of ceramic media during cleaning (See Figure 4-3a). In the FilterPure design, colloidal silver is mixed in water which is then added to the dry ingredients (processed clay and saw dust) and mixed further prior to molding and firing the filter. This is distinct from the IDEAC procedure where the silver is painted on after the filter is fired. For additional details on the manufacturing procedures used by both IDEAC and Filter see Appendix L.

4.5 Field Site

The chosen site for this research needed to be within a reasonable distance from the laboratory facilities in Santiago where biological testing would occur, so that samples could be collected, transported, and analyzed within the 30 hour holding time limitation recommended by EPA (EPA 1997). A rural community was preferred over an urban or peri-urban area in order to avoid confounding microbial performance with other factors such as the presence of chlorine which is often used in municipal water treatment plants. Very few if any rural communities in the Dominican Republic have centralized water treatment systems. In addition, a community where bottled water consumption is low was preferred since in the Dominican Republic as much as 55% of the population uses bottled water as their principal source of drinking water (ENDESA 2007). Bottle water is more available and less expensive in urban and peri-urban areas and therefore it is assumed that consumption of bottled water is lower in rural areas. Finally the individual with primary responsibility for collecting data in the community over the course of the study lived along the road connecting Santiago with Puerto Plata to the north. Therefore it was decided that a community in the area along this road would be ideal. Utilizing contacts in the area the community of La Tinajita was identified (See Figure 4-4 and Appendix M: Site Location Maps).

Figure 4-4 Map of the Dominican Republic and the research site location. Map shows the location of La Tinajita in relation to the largest cities, Santo Domingo (national capital) and Santiago. Also shown is Puerto Plata the provincial capital of the province where La Tinajita is located and the two communities where the filters are manufactured and sold, Higuerito (FilterPure) and Yamasa (IDEAC).

4.5.1 Community Profile

La Tinajita (19˚34'N 70˚37'W) meaning "small water tank" in Spanish is a paraje which is the lowest level of political division in the Dominican Republic. The community has a population of 263 and is located in the municipality of Pedro Garcia in the province of Puerto Plata. The community is accessed by a single lane dirt road from the west that connects to the carretera turistica (tourist highway) as it is locally known. This was formally the principal route connecting the 2nd largest city in the north, Santiago, with the port city of Puerto Plata. Since the construction of a tunnel enabling a more direct route, this highway has fallen into disrepair. Consequently the road obtained its name from the tourists escaping Santiago on weekends for a scenic drive or bike ride. A more direct route to Puerto Plata has had important implications for La Tinajita and the inhabitants of this area. Funds for infrastructural improvements have been diverted from this area and the economy has suffered. Table 4-9 shows the services available in La Tinajita.

Table 4-9 Services available in the community of La Tinajita.

Electricity	Electricity to the community is pirated from the grid and service is intermittent.
Sanitation	No centralized system (see Table 4-11 for details)
Solid Waste	No collection, each household manages disposal. Trash is often burned in the dry season or when a significant amount has accumulated.
Water Supply*	1. semi-protected spring with water distribution system and storage
	2. unimproved spring with water distribution system and storage
	3 unimproved spring with water distribution system and storage
	4. unimproved spring
	5. river
Education	One room public primary school (grades 1-4)
Medical	None
Commercial	Three households operate small retail shops selling basic food stuffs and alcohol. Pickup trucks pass weekly selling live chickens, produce and sundries.

***-For more details see Appendix N: Community Water Sources.**

The nearest medical facility to La Tinajita is a rural clinic, located 1.8 miles (5 minutes by vehicle or 35 minutes walking) away. The clinic provides medication, vaccination, prenatal care, and other medical attention free of charge to rural communities in the immediate vicinity. A hospital is located 3.5 miles from the community in the municipal capital, Pedro Garcia. This hospital provides the same services as the clinic, and therefore any patients requiring acute medical attention must travel one hour to Santiago. Therefore, the rural clinic is the primary medical care facility used by La Tinajita community members. Comparing rainfall data with clinic records, there seems to be a correlation between the incidence of respiratory and skin infections and lower rainfall (see Appendix O). Appendix O has graphs for diarrheal disease, parasitosis, and gastritis as well as influenza and nasal/throat infections, which are the most common water related illnesses.

4.5.2 Filter Distribution

Fifty paraboloid CWFs were ordered from FilterPure and fifty frustum CWF were ordered from IDEAC for a total of 100 filter units (see Figures 4.3a and 4.3b). Extra filters were ordered to account for breakage during transit and during the study period. All members of the community as well as leaders outside the community (e.g. workers at the clinic) were provided with the appropriate contact information on how to obtain more filter units and parts after the study has concluded. Each manufacturer was requested to provide filters from the same batch (if possible) using the same clay and burnable sources for each filter. The filter units were packaged and transported from the manufacturing facilities to the rural clinic where they were stored until they were distributed. Following the recommendations of the operators of the clinic the decision was made not to charge for filters. Filters were distributed to the community on Sunday August 29th and Sunday September 5th 2010. For more details on the training and distribution process see Appendix P. . Every inhabited household in the community received one filter, with the filter types being randomly assigned A total of 59 households participated and approximately equal numbers of FilterPure (n=30) and IDEAC (n=29) filters were distributed.

4.6 Methods

The research methods described below were approved by the Institutional Review Board of the University of South Florida for human subject research under IRB#: Pro00001074 on May 12, 2011. See Appendix Q for the appropriate documentation. Table 4-10 shows an overview of the Field Data Collection Schedule.

Table 4-10 Data collection schedule for longitudinal field study in La Tinajita.

Year	2010							2011											
Month	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Surveys																			
Baseline	x																		
Regular					x			x				x				x			
Milestone													x						
Tests																			
Water Quality						x	x	x		x		x	x	x	x	x	x		
Hydraulic						x	x			x	x	x	x	x	x	x	x		

Note: Baseline Survey and Milestone Survey conducted in all 59 households. Regular survey conducted at a minimum of 20 randomly selected households. Water Quality Monitoring: Raw and filter water samples collected in all houses surveyed. Hydraulic tests includes falling head tests conducted in 6 households (3 Potters for Peace filters and 3 FilterPure Filters) and first hour flow rate tests conducted in 20 randomly selected households.

4.6.1 Surveys

A baseline survey was conducted in La Tinajita between June 21st and 24th of 2010. The information collected in this survey included household demographics, characteristics and services, water source, water collection, consumption, and treatment information, perceptions about water quality. Results are presented in Table 4-11 and other select information is provided in Appendix R. A regular survey was done quarterly in twenty randomly selected households; these surveys included all the same information except for the household demographics and characteristics. A year after the baseline survey was done a milestone survey was conducted in each household. This survey was more in-depth and included questions about the household's opinions on the filters. Appendix S provides an overview of these surveys and discusses user acceptability in more depth.

Table 4-11 Results of the baseline survey conducted in La Tinajita.

Number of Households*	58	Included in Baseline Survey	53
Average Household Size	4.6		
Population • Less than 5yrs • 5-15 yrs. • 16-25 yrs. • 26-55 yrs. • Over 55 yrs.	267 33 (12.4%) 73 (27.3%) 65 (24.3%) 72 (27.0%) 24 (9.0%)	Head Household Education • None • Primary • Junior High • High School • Tertiary	 4% 66% 7.5% 15% 7.5%
Primary Drinking Water • Spring • Rainwater • Bottled Water	Season Wet / Dry 15% / 65% 68% / 5% 17% / 30%	Water Collector • Female head • Male head • Young girl • Young boy • Other	 64.6% 12.3% 7.7% 3.1% 12.3%
Water Access • Outdoor connection • Indoor connection • None	 37(70%) 8(15%) 5(9%)	Sanitation Access • Flush toilet • Pit latrine • None/shared latrine	 1(2%) 44(83%) 8(15%)
Water Safe to Drink • Yes • No • Do not know • No Response	 27 (51%) 23 (43%) 2 (3.8%) 1 (1.9%)	Water Treatment Methods • Boiling • Chlorine • Filter • Other • None	 32(60% 17(32%) 44(83%) 4(7.5%) 2 (3.8%)
Water Storage Method • Plastic bucket • Barrel or Drum • Clay pot • Jerry Can • Plastic Bottles • No Container	 12% 46% 5% 11% 18% 7%	Reported Water Demand • Drinking • Cooking • Cleaning • Washing • Bathing	(liters/hh) 7.5 18 117 300 95

***-When the Baseline Survey was conducted in June 2010 there were 58 households. Another house was built in the community that summer and therefore 59 filters were distributed.**

4.6.2 Water Sampling

Water samples were collected in a randomly selected subset of households. The objective was to obtain samples in at least 20 households, however due to slower than expected filtration rates it was not always possible to meet this objective in the allotted sampling time period because samples had to be delivered to the laboratory by 5pm the same day they were collected. Raw water samples were collected from inside the filter reservoir (See Figure 4-2) with a 250-ml stainless steel cup that was rinsed in between raw water samples with filtered water. Filtered water samples were collected from the tap on the side of the plastic bucket with sterile 500mL Whirlpak® sample bags. Care was taken to not contact the water being sampled with hands of the sample collector. Samples were taken to the laboratory at the Instituto Superior de Agronomia in Santiago for analysis. The microbial quality of samples was analyzed following membrane filtration Method 1604 (EPA 2002) for the simultaneous detection of total coliforms and E. coli. Turbidity measurements were also performed on all water samples. Turbidity was measured in the field and laboratory using a portable turbidimeter model 2100Q (HACH Company, Loveland CO) following EPA Method 180.1. Initially information was also collected on the temperature, pH, conductivity, and total dissolved solids of the water samples. However this was discontinued after the first two rounds of sampling as the values did not fluctuate significantly and/or deviate out of the acceptable ranges (when applicable). Appendix T has a complete list of the water quality parameter guidelines used by the government of the Dominican Republic and the World Health Organization.

4.6.3 Hydraulic Tests

There are various ways to measure the hydraulic performance of CWF. Laboratories often measure the time it takes to filter a given volume of water under constant head, called the "standing head test." This requires complicated equipment and is not appropriate for in-situ field measurements. Another way to measure hydraulic performance is to measure the volume filtered after a set amount of time (without refilling) or the time it takes to filter a set volume (without refilling). This test is called a "falling head test" because the hydraulic head is changing over the course of the measurement. It can also be used to calculate the hydraulic conductivity of the filter material. The method used for quality control in all 20 filter factories that participated in a 2009 survey is the first hour flow rate, a type of falling head test. In this test the filter is filled to the top (careful not to overfill), and the volume of water filtered after one hour is recorded as determined by the volume collected in the storage bucket (Raynor 2009). Both types of falling head tests were conducted in La Tinajita, however, only the first hour flow rate results will be presented and discussed in this chapter. This was because the filters performed at such a slow rate, it was impossible to collect falling head tests from 20 households during the 6 hours allotted for sampling, as some falling head tests took more than 24 hours to complete. Therefore, the falling head test was eventually discontinued.

4.6.4 Focus Group

One year after filter distribution, two different focus group meetings were held. The week prior to the focus group meetings the female head of household from each house was asked to attend the focus group to share their opinions and experiences. An introduction was given by the author explaining the connection between the filter manufacturers, the University of South Florida, and the researchers. The stated objective was to discuss what each individual thought about the filter they received. Participants were divided into two groups based upon filter type; however the participants were not told that this was the basis for assigning them to either group. Each group contained eight women who were asked at least 15 questions (scripted) in a discussion style format allowing for additional questions and discussion (Krueger and Casey 2009). Women also participated in 2 activities, briefly described in Table 4-12. The voice recording equipment available was unsuitable for the location of the focus group meetings and therefore no transcripts exist and rather a summary of the notes taken by the researchers is provided in Appendix U. The qualitative data obtained from the focus groups and the household surveys are described in the discussion section.

Table 4-12 La Tinajita focus group discussion questions and activities.

Who had seen a ceramic filter before this project? Where did you see it?
Think of the time when you first saw your filters—What did you think?
How have your opinions about your filter changed?
Do you use your filter?
What do you use the filtered water for?
What are the water sources in the community?
Activity#1: The women were then asked to place these in order of most preferable to least preferable using pictures of each. Each woman was asked to explain her choice.
Activity #2: The women were then asked to arrange the pictures from best water quality to worst water quality.
In the future would you buy a filter if yours broke? If so how much would you pay?
What are the things that you like about your filter?
What are the things that you do not like about your filter?

4.7 Results and Discussion

4.7.1 Turbidity Removal by Filters

Turbidity is an easily measured physical parameter of water and can be used to determine the relative risk of bacterial contamination. Pathogens are often sorbed to particles which can serve as a substrate or protective environment for these organisms. WHO recommends drinking water have a turbidity of less than 5 nephelometric turbidity units (NTU). The turbidity of the raw water added to most filters was very low (median = 1.38 NTU). This is due to two issues: first, during the wet season (November thru May) 68% of households use rainwater, which has very low turbidity, for the filter. Second, during the dry season (June thru October) 65% of households use spring water for their filter. Spring water turbidity is considerably lower in the dry season, average 4.5 NTU, versus the wet season, average 8.6 NTU. Average filtered water turbidity for both the paraboloid and frustum filters is presented in Figure 4-5. The raw and filtered water almost always had turbidity of less than 5 NTU. The average percent removal of turbidity was 38.1% in the paraboloid filter and 29.0% for the frustum filters.

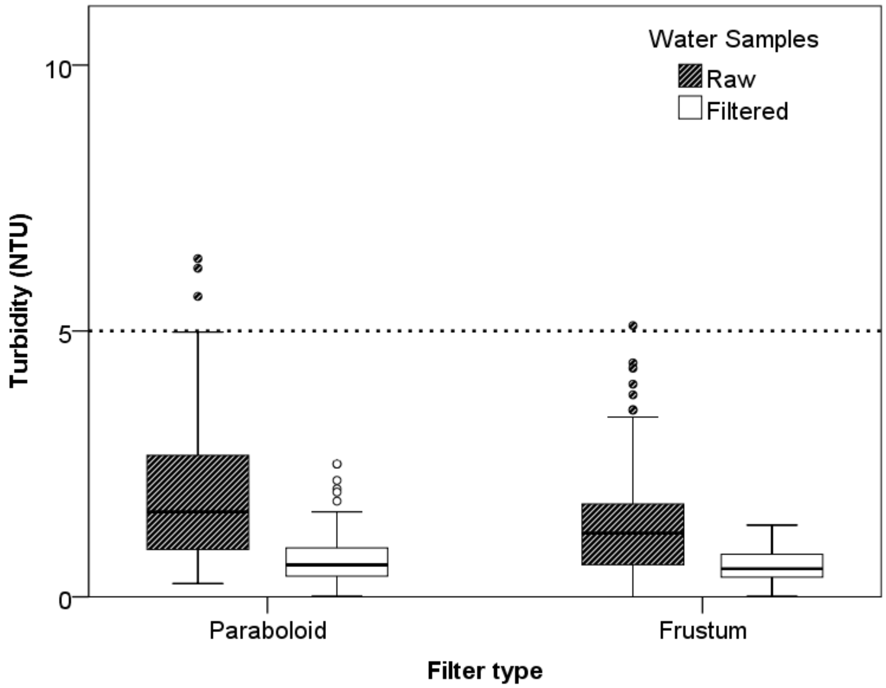


Figure 4-5 Average raw and filtered water turbidity for the paraboloid and frustum filters. Paired samples from all 59 filters were collected: 145 and 97 samples from paraboloid and frustum filters respectively. The dashed line represents the maximum recommended turbidity level for drinking water, which is 5 NTU (WHO 2011). Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

Figures 4-6 and 4-7 show the turbidity of raw and filtered water, for the paraboloid and frustum filters respectively, over the course of the research. In only one week (week #25) out of eleven weeks when turbidity measurements were taken was there a statistically significant difference between the filtered water samples of the paraboloid and frustum filters (p=0.009). There was however, a statistically significant difference (p=0.004) in the average weekly raw water turbidity for the paraboloid filters in the wet season (represented by weeks 10 thru 38) compared to the dry season (represented by weeks: 47, 52, 56, and 59), with the wet season having higher raw water turbidity It is unclear why this was the case for households using paraboloid filters but not frustum filters since the primary water source cited by households was similar between households in the different seasons (See Table 4-13).

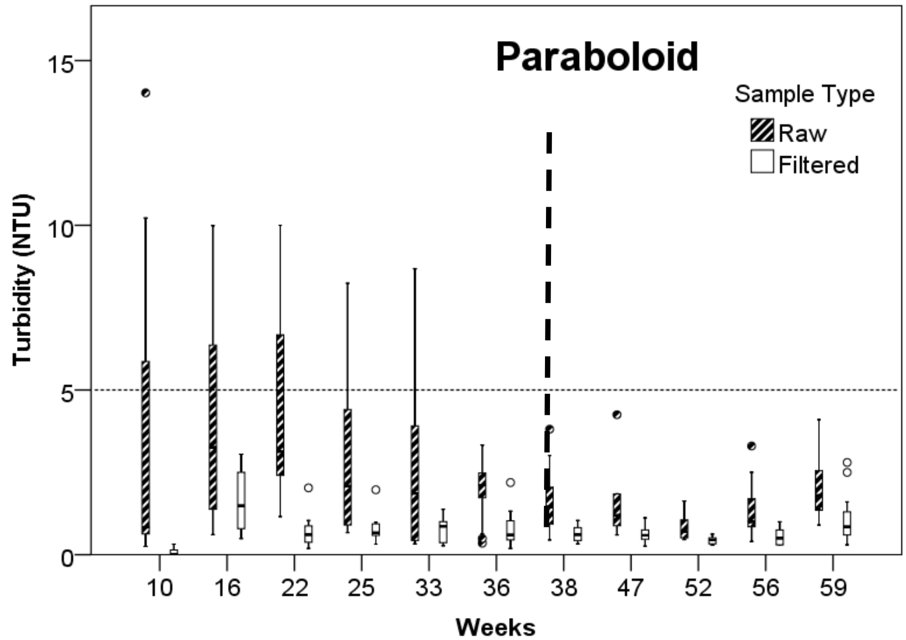


Figure 4-6 Turbidity of raw and filtered water for the paraboloid filters by season. Data was collected during the wet season (weeks 10 through 40) and dry season (weeks 41 through 59). The horizontal dashed line represents the maximum recommended turbidity level for drinking water, which is 5 NTU (WHO 2011) and the vertical line separates the wet and dry season. Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

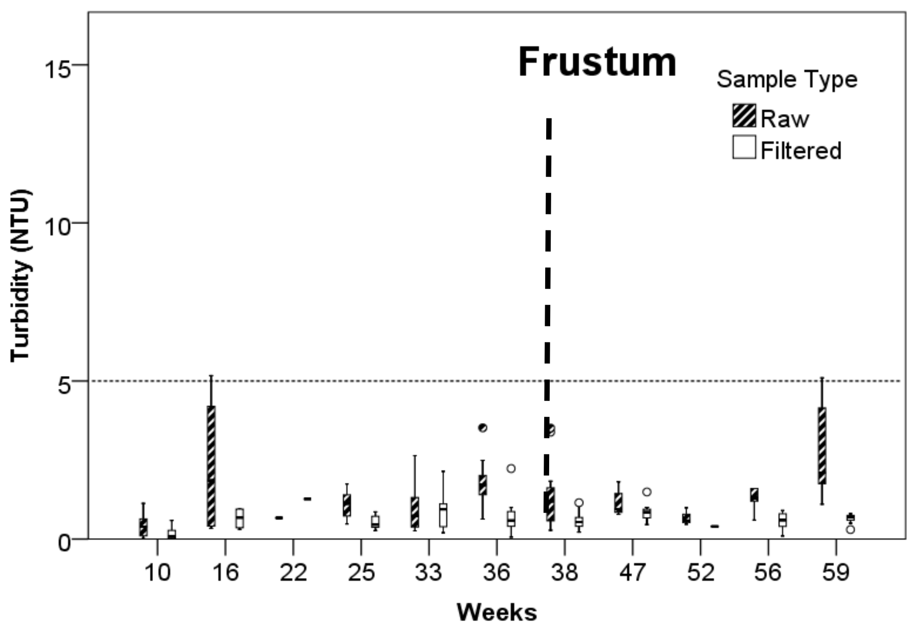


Figure 4-7 Turbidity of raw and filtered water for the frustum filters by season. Data collected during the wet season (weeks 10 through 40) and dry season (weeks 41 through 59). The horizontal dashed line represents the maximum recommended turbidity level for drinking water, which is 5 NTU (WHO 2011) and the vertical line separates the wet and dry season. Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

Table 4-13 Primary water source by season and the filter type used by each household.

Water Source	Wet Season		Dry Season	
	Paraboloid	Frustum	Paraboloid	Frustum
River	2%	2%	3%	2%
Spring	44%	43%	40%	46%
Rainwater	41%	43%	39%	35%
Bottled water	13%	13%	18%	17%

Turbidity was the same or higher in 55 filtered water samples of the 242 paired samples (raw and filtered water). In 21% (30 out of 145) of paraboloid and 25% (25 out of 97) of frustum, filtered water samples had higher turbidities than the raw water added to the filter. Of these 55 cases the raw water turbidity was very low (less than 1 NTU) in only 9 instances (paraboloid) and 3 instances (frustum). This is important as turbidity was highly correlated to the presence of E. coli and total coliforms (p values of 0.012 and 0.021 respectively). Therefore if the filtered water samples have higher turbidity there is a concern that the microbial effectiveness may not be optimal.

4.7.2 Microbial Removal by Filters

Due to the slow filtration rates and the limitations in public transportation from the field site to the laboratory in Santiago, there were limited samples that had enough volume to run replicates and therefore performing dilutions on the raw water was not possible. As a consequence, a significant number of the results for the raw water came back as too numerous to count (i.e. greater than 200 CFU per agar). Therefore it was not possible to calculate percent removal for a significant number of samples. Accordingly, the microbial effectiveness of the filters was determined by analyzing the filtered water quality alone. Considering all 571 filtered water samples analyzed in this research and comparing to the studies in the literature there was a statistically significant difference in the averages for the number of filtered water samples that met the WHO standard of 0 CFU per 100mL and the number that fell into the low to intermediate risk category (less than 10 CFU). Table 4-14 presents the results of the samples from La Tinajita to the averages from the longitudinal and cross-sectional field studies. The filters in this research performed significantly worse with regard to the filtered water quality compared to studies from the literature. It is unclear what would cause such a large difference, although it is unlikely that such a difference could be attributed to user behavior alone.

Table 4-14 World Health Organization standards and ceramic filter field studies. The WHO standard is 0 CFU/100mL and Low to Intermediate Risk categories is up to 10 CFU/100mL.

Field Studies	Low to Intermediate Risk Category	WHO Standard
Cross-sectional	92%	76%
Longitudinal	75%	55%
La Tinajita	56%	37%

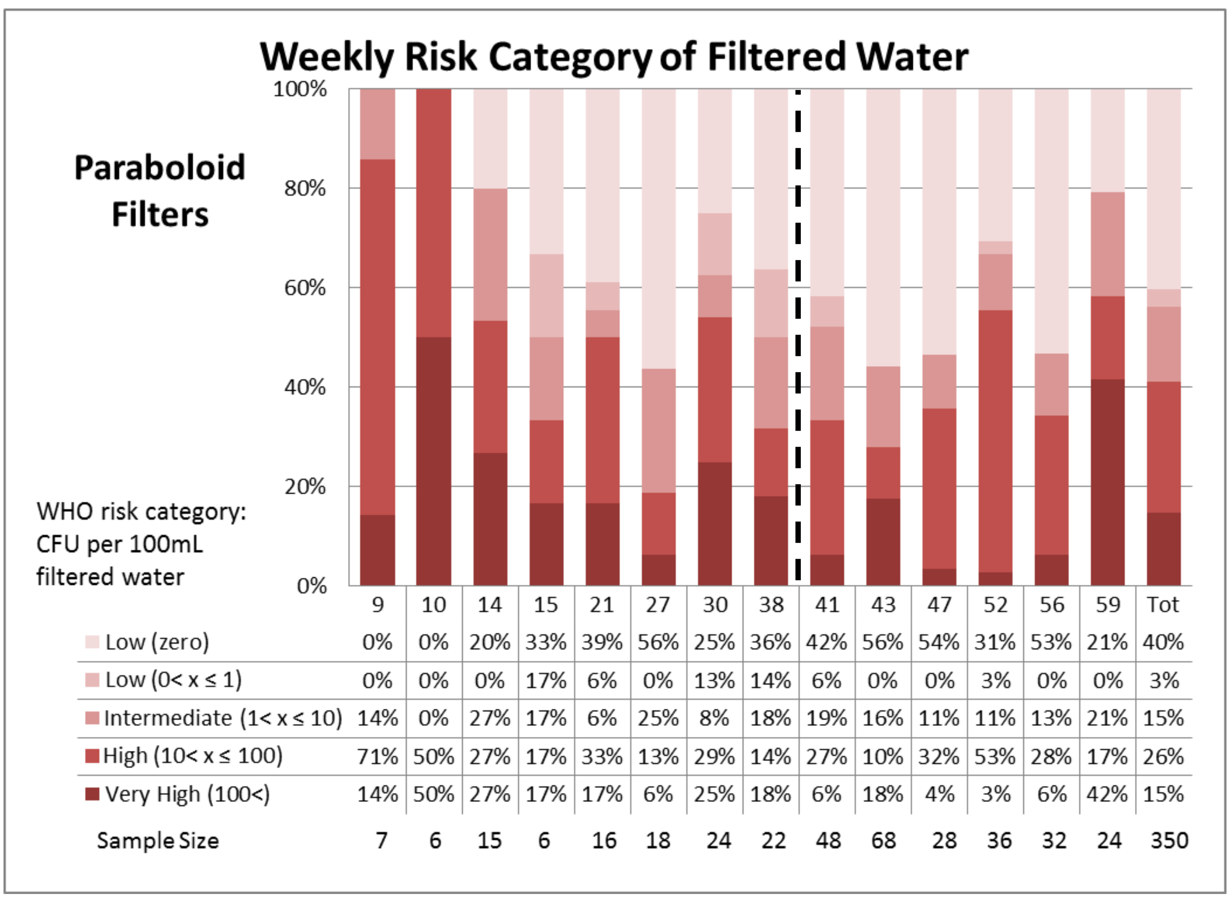
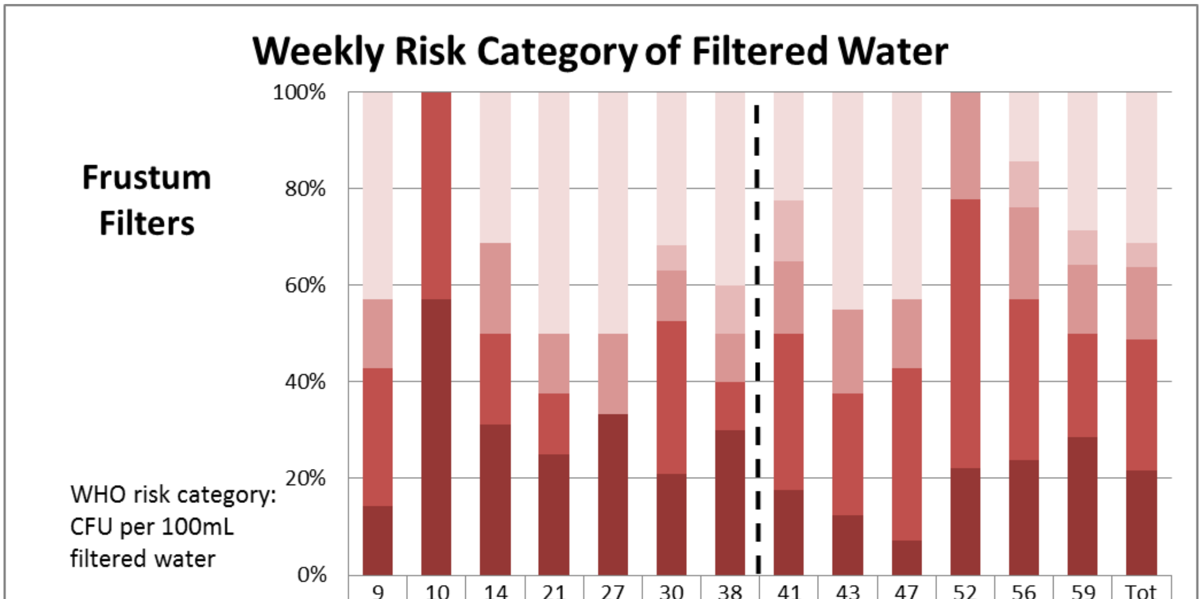


Figure 4-8 WHO risk categories for filtered water samples from the paraboloid filters. Samples were taken over 59 weeks of the research. The vertical dashed line divides the weeks of the wet (9-38) and dry(41-59) seasons. The total for all weeks is the last bar graph "Tot" and the sample size for each week is shown at the bottom.

Figures 4-8 and 4-9 show a disaggregation of the WHO Risk Categories by week for both filters. Over the 59 weeks of sampling, 40% of the paraboloid filter samples met WHO guidelines for 0 CFU per 100mL sample, while only 31% of the frustum filter samples did (p=0.002). In addition the difference between the filtered water samples that were very high risk for the paraboloid (15%) and frustum (22%) was statistically significant (p=0.003). Therefore it can be said that there was a statistically significant difference in performance between the paraboloid and frustum filters, with the former producing more filtered water samples that met the WHO guideline and also had less filtered samples that were of very high risk compared to the frustum filters.



	9	10	14	21	27	30	38	41	43	47	52	56	59	Tot
Low (zero)	43%	0%	31%	50%	50%	32%	40%	23%	45%	43%	0%	14%	29%	31%
Low (0< x ≤ 1)	0%	0%	0%	0%	0%	5%	10%	13%	0%	0%	0%	10%	7%	5%
Intermediate (1< x ≤ 10)	14%	0%	19%	13%	17%	11%	10%	15%	18%	14%	22%	19%	14%	15%
High (10< x ≤ 100)	29%	43%	19%	13%	0%	32%	10%	33%	25%	36%	56%	33%	21%	27%
Very High (100<)	14%	57%	31%	25%	33%	21%	30%	18%	13%	7%	22%	24%	29%	22%
Sample Size	7	7	16	8	6	19	20	40	40	14	9	21	14	221

Figure 4-9 WHO risk categories for filtered water samples from the frustum filters. Samples were taken over 59 weeks of the research. The vertical dashed line divides the weeks of the wet (9-38) and dry (41-59) seasons. The total for all weeks is the last bar graph "Tot" and the sample size for each week is shown at the bottom.

Both of the filter designs had significant filtered water samples that failed to meet WHO guidelines- 60% of the paraboloid samples (n=210) and 69% of the frustum samples (n=152) tested positive for E. coli in the filtered water. As previously mentioned, in the literature often poor microbial performance is attributed to filter hygiene and/or user issues (Lantagne 2001b; Roberts 2004; Baumgartner et al. 2007; Kallman et al. 2011). Therefore a short study was performed to address the potential of recontamination by collecting samples directly off of the filter membrane. This research is described in the subsequent section.

4.7.3 Recontamination Study

For this study, raw water samples were collected from the inside of the ceramic filter reservoir and "filtered water" samples were collected from the tap on the side of the plastic bucket. We believe this accurately represents the quality of water the filter is challenged with and the quality of water the users will ingest. In the field studies raw water was often collected from household water points (Kallman et al. 2011) or from community sources (Hwang 2006). However, this may not be representative of the actual quality of the water that the filter must treat, especially if the collected water is deposited in a larger storage container (e.g. 55-gallon barrel) prior to addition to the filter. In such a scenario the collected water is essentially decanted and hence will have lower turbidity than water that is collected from a tapstand and directly added to the filter. In addition, the author's knowledge of all studies trying to evaluate in-situ filter use have collected filtered water samples from the outlet tap on the side of the bucket.

Despite the difficulties in quantifying the raw water quality, it is clear from the raw water data and the filtered water data (Figure 4.8 and 4.9) that the performance over time for individual filters has been inconsistent. Eleven filters were identified as functioning improperly (with respect to flow rate and/or microbial effectiveness) and as a result were replaced with acceptable filters.

Initially the decision was made to collect the water from the bucket tap as opposed to from the filter membrane directly in order to characterize the "field performance" of the filter and also maintain samples that are representative of what users are consuming. As a result it was unclear if the inconsistency in filter performance was due to actual filter membrane performance or rather due to improper filter maintenance, user related issues (such as overfilling), or a combination of three. In order to fill this gap in knowledge a pilot study began in June 2011 and samples were collected once a month for three months. To isolate the source of contamination and evaluate both the filter membrane as well as comprehensive filter field performance the following water samples were taken:

1. Raw water collected from inside the ceramic filter reservoir (i.e. "Raw")
2. Filtered water collected directly from the ceramic membrane (i.e. "Direct drip")
3. Filtered water collected from bucket tap (i.e. "Tap")

In addition, in order to try and characterize the status of the surfaces that the water comes into contact with prior to being consumed, surface sampling using 3M Quick Swabs was performed. Follow the procedures outlined by the manufacturer (3M Microbiology, 2003), the bottom of the storage receptacle and the interior surface of the water tap were swabbed. The areas swabbed are approximately 226 cm^2 (± 2 cm) and 6 cm^2 for the bucket[22] and tap respectively. The above samples were taken in June (18 households), August (15 households),

[22] This area corresponds to half of the bottom of the bucket. This was chosen because the microbial load of some buckets was so great that swabbing the entire bottom would have yielded plates that were too numerous to count, yet any less area would require using sterile

and September (13 households). The sample size is insufficient to draw statistically significant conclusions; however an analysis of the results yielded important conclusions.

From Figures 4.10 and 4.12 it is clear that significant removal of E. coli and total coliforms from raw water is occurring. However, when comparing the median values for total coliform removal between the Direct Drip water and water from the Tap (See Figure 4-12), we see that the median concentration is higher for the Tap 42 CFU/100mL compared to the Direct Drip 12 CFU/100mL. This suggests that the water coming off of the filter (Direct Drip) is of higher quality as compared to the water leaving the Tap. In 24% of samples (11 out of 44) the concentration of E. coli was greater in the water from the tap than in the raw water. In three of these 11 samples, the Direct Drip water had a higher E. coli concentration than the water collected from the Tap. In 11% of the samples (5 out of 45) the concentration of total coliforms was greater in filtered water collected at the Tap compared to the Raw water. In all five samples the Direct Drip water had lower total coliform concentration compared to the water collected at the Tap. These findings suggest that in some cases the filter unit is actually adding coliforms to the water passing through the filter and in other cases the water is picking up contaminants after filtration (see Table 4-15). This phenomenon has been observed in the laboratory. For example, Bielfeldt and colleagues (2009) demonstrated that after treating water containing high concentrations of E. coli the CWFs contributed bacteria into subsequent clean water passing through the filters.

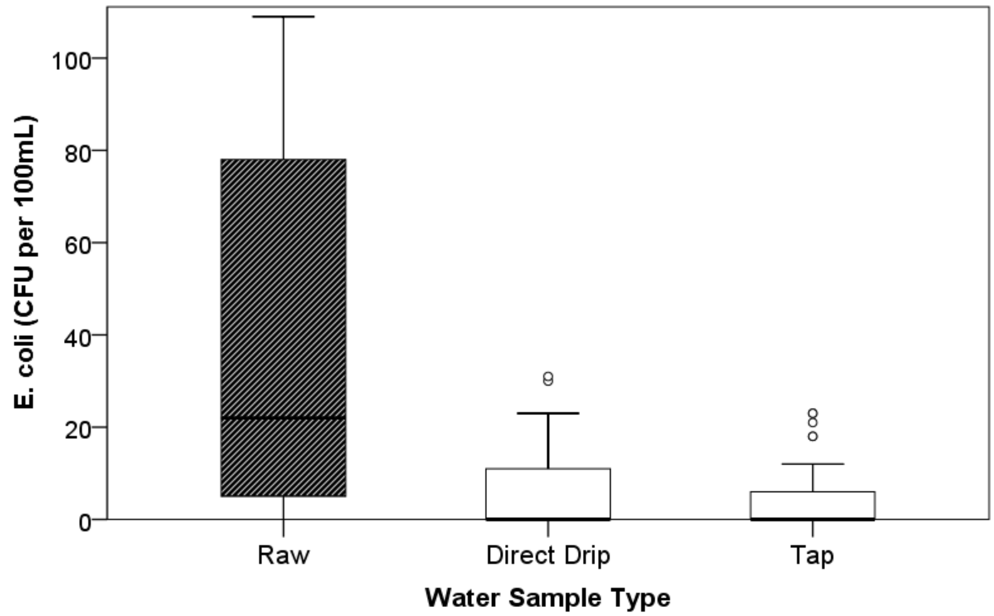


Figure 4-10 Quantity of E. coli per 100 mL water sample. Raw water was collected from inside the ceramic filter (Raw), directly as it dripped off the filter before contacting any surfaces (Direct Drip), and at the tap in the side of the storage bucket (Tap). Sample size is the same for each (N = 45). Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

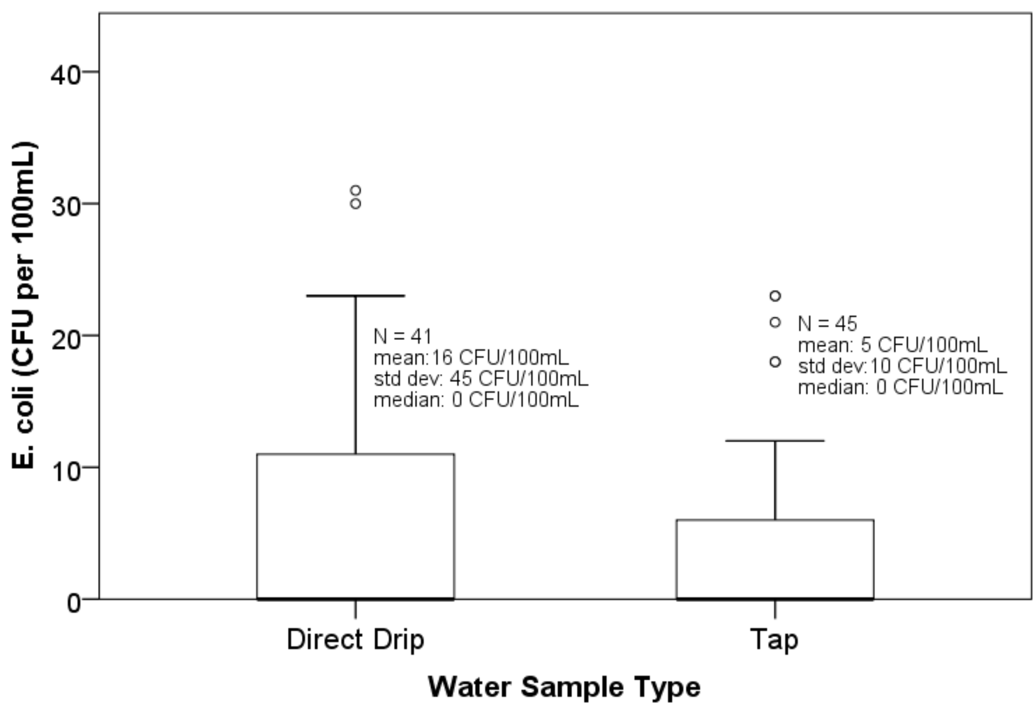


Figure 4-11 Quantity of E. coli per 100 mL sample of Direct Drip and Tap water. The median, mean and standard deviation is shown for each. Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

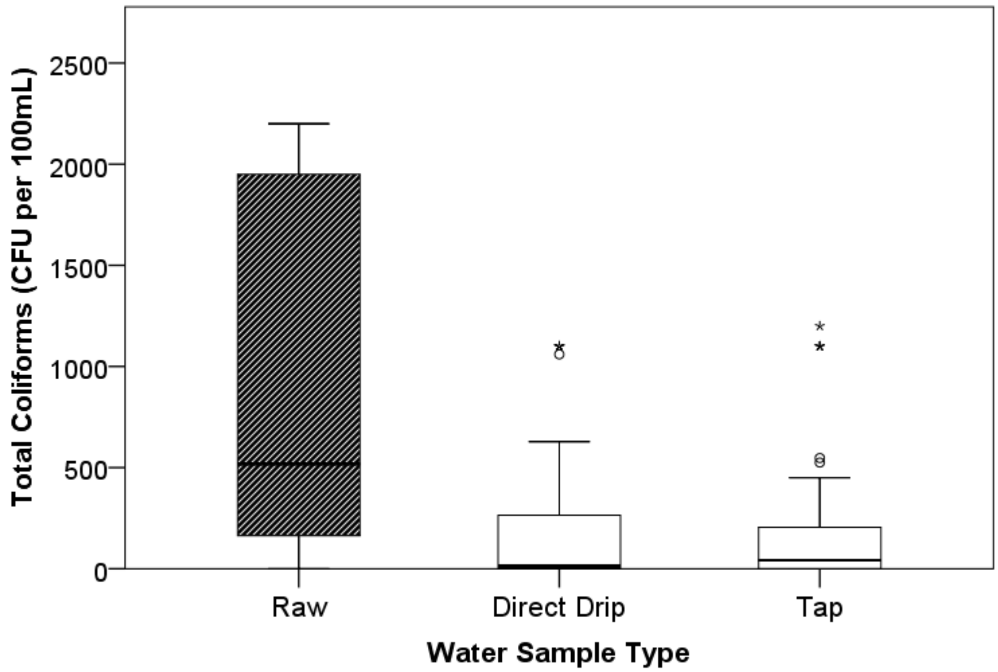


Figure 4-12 Quantity of total coliforms per 100 mL water sample. Raw water was collected from inside the ceramic filter (Raw), directly as it dripped off the filter before contacting any surfaces (Direct Drip), and at the tap in the side of the storage bucket (Tap). Sample size is the same for each (N = 45). Error bars represent the 95% confidence interval and the statistical outliers are shown as circles with extreme outliers as stars.

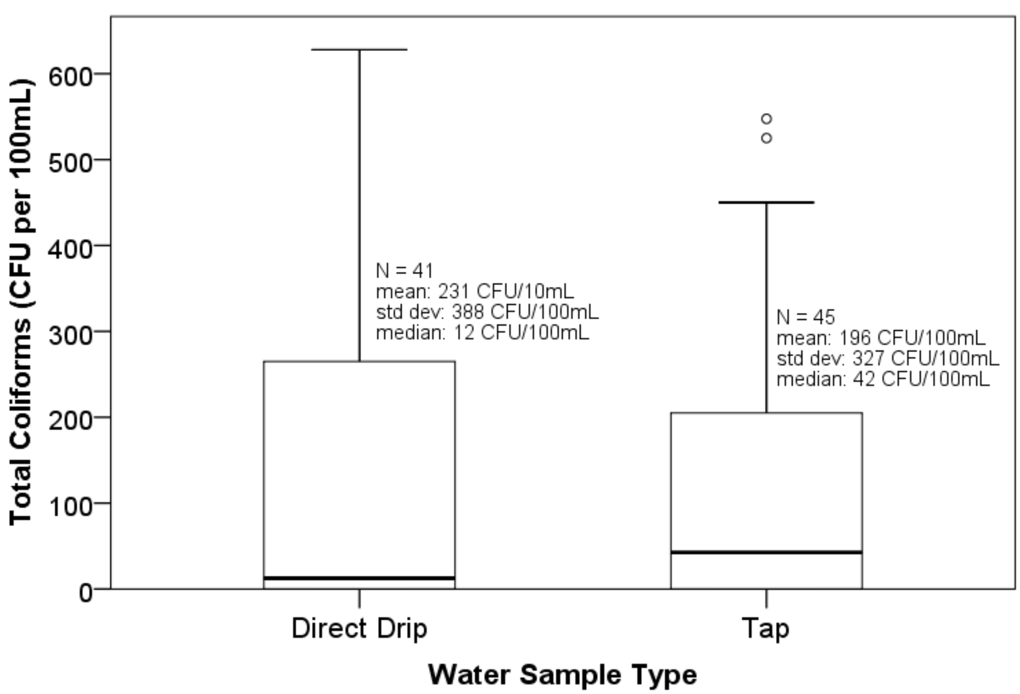


Figure 4-13 Quantity of total coliforms per 100 mL sample Direct Drip and Tap water. The median, mean and standard deviation is shown for each. Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

Table 4-15 presents a comparison between paired water samples collected at different points in the treatment process (Raw, Direct Drip, and Tap). Refer back to Figure 4-2 for a schematic of the ceramic water filter and the sample locations. Column one of Table 4-15 presents the number of water samples collected at the Tap that had greater concentrations of total coliforms and E. coli than Raw water collected from the same filter (i.e. paired samples). Similarly column two of Table 4-15 shows the number of Direct Drip samples that had higher concentration of contaminants that Raw water. Note that the differences are presented in such a way as to be counter intuitive. For example, it is expected that Direct Drip would have lower concentration than Raw water.

Table 4-15 Comparison of microbial water quality from the ceramic water filter. The number of colony forming units is compared between paired samples collected at different locations on the same filter including: Raw, Direct Drip, and water obtained from the Tap.

	Raw ≤ Tap	Raw ≤ Direct Drip	Direct Drip ≤ Tap
Total Coliform	11% (5)	13% (6)	49% (22)
E. coli	24% (11)	31% (14)	69% (31)

Baumgartner and colleagues (2007) determined that removal was lower in filters that were overfilled, which could explain the phenomenon observed in this research. It is also possible that coliforms are growing on the inside of the storage container or tap orifice. Figure 4-14 and 4-15 present the data from the surface sampling using 3M Quick Swabs. From these figures it is clear that a statistically significant amount of contamination was present on the Tap Orifice. This would explain the large number of samples that had greater concentration of contaminants in the water collected from the Tap compared to the water collected off the filter (Direct Drip) (See Table 4-15). It is important to note that Figure 4-14 present the number of viable colonies that were extracted from the swabs, but does not account for the area swabbed. Figure 4-15 normalizes the data per square centimeter swabbed. To put these values into context, the ISO standards used for the preparation of sterile materials, assigns risk categories based on swabbing 30 square centimeters. The risk categories are as follows: >30 CFU (Low), >5 CFU (Intermediate), and >100 CFU (High).

To the author's knowledge no prior study has quantified the presence of microbial contaminants on the surface of filters. It is believed that this may be a significant source of contamination to the water passing through the filter. The risk of contamination to the tap orifice is recognized by the users, and many households cover the tap with a plastic bag or rag. It is unclear if this increases or decreases the risk of contamination. This is discussed further in Section 4.7.5.

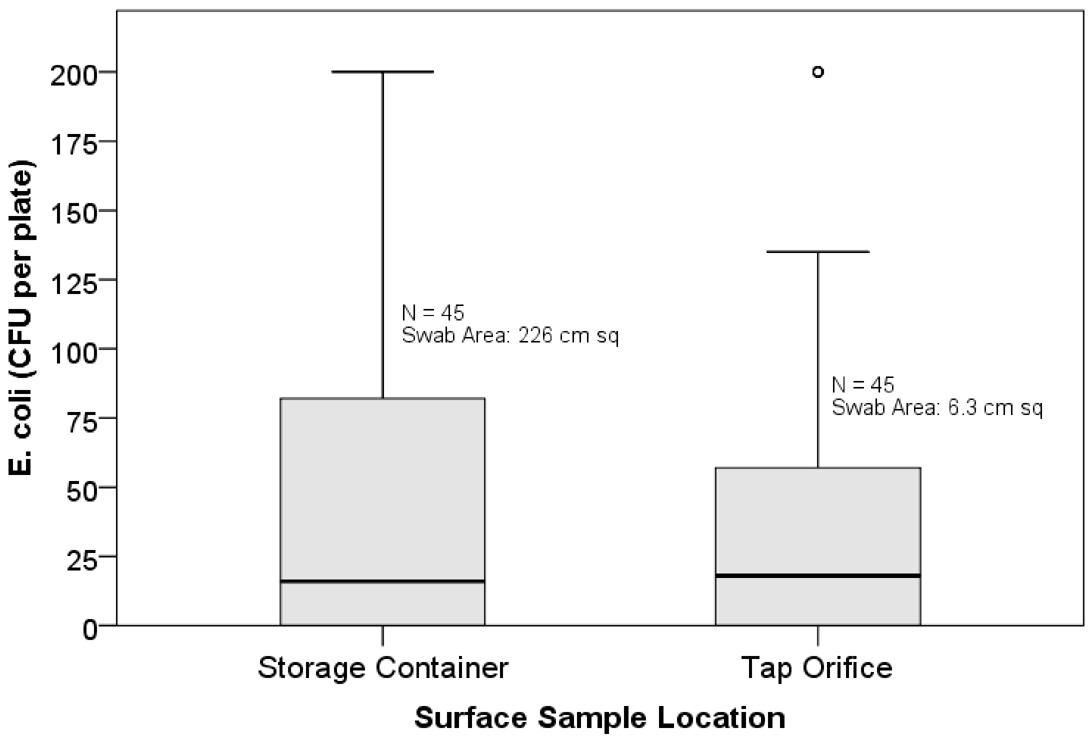


Figure 4-14 Viable E.coli colonies on the inside surface of the filter. Samples were obtained by swabbing storage container (226 square centimeters) and the tap orifice (6.3 square centimeters). Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

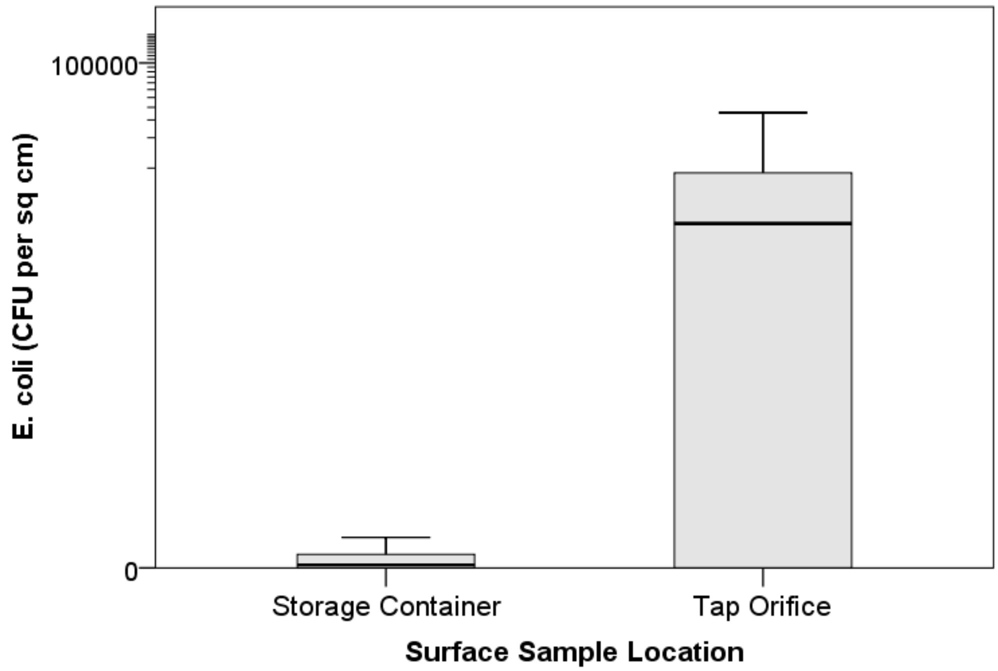


Figure 4-15 Viable E.coli colonies per square centimeter of surface swabbed. Samples were obtained by swabbing the inside of storage containers and the tap orifices. 45 paired samples were obtained over three months. Error bars represent the 95% confidence.

4.7.4 First Hour Flow Rate

Howard and Bartram (2003) suggested that the minimum volume of water necessary to meet the drinking water needs of the average person under average conditions is 3 liters per person per day. The Dominican government has a less conservative figure of 2-2.5 liters per person per day or the equivalent to 3% of the average weight of the person. Considering the average household size in La Tinajita (4.6 people), the minimum water requirement for the average household is between 10 (using the Dominican figure) and 15 liters per day using Howard and Bartram estimates. It is questionable therefore whether the filters evaluated in this research have sufficient hydraulic efficiency to meet these minimum household requirements and more importantly the expectations of the users. Appendix T has a discussion of the issues that are believed to affect user acceptability of the filters in this research.

Figure 4-16 shows the results of the average flow rates from the first hour flow rate measurements taken over the course of the research and Figure 4-17 shows the results of the first hour flow rate over time. Only 17 filters had observed flow rates that were greater than or equal to 1,000mL/hr., 5 frustum and 12 paraboloid filters. The average flow first hour flow rate was 401 (± 281) mL per hour and 616 (± 281) mL per hour for the frustum and paraboloid filters respectively. It is important to note that the first hour flow rate represents the best case scenario (i.e. the full filter flow rate is the fastest flow rate). Therefore the maximum amount of water that could be produced in a day by the average filters, assuming users constantly refilled their filters during all waking hours (20 hours), would be between 8 and 12 liters per filter per day. Therefore it is probable a singled filter per household would not produce enough water to meet the minimum basic requirements of the average household.

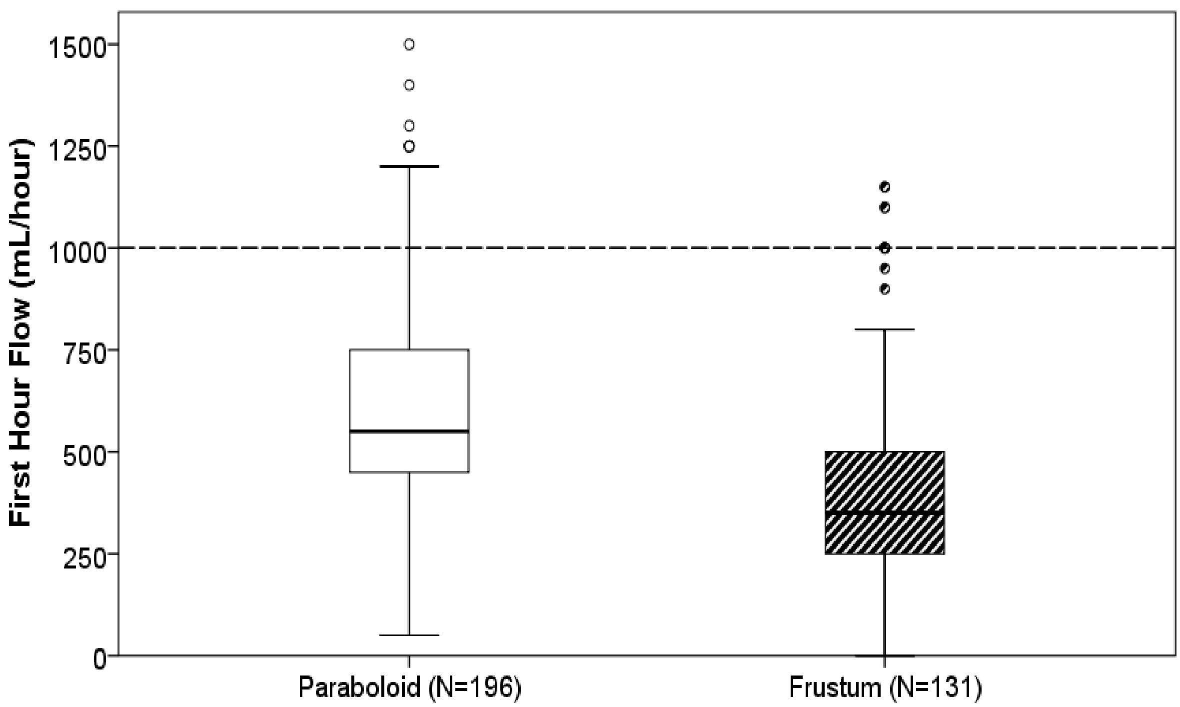
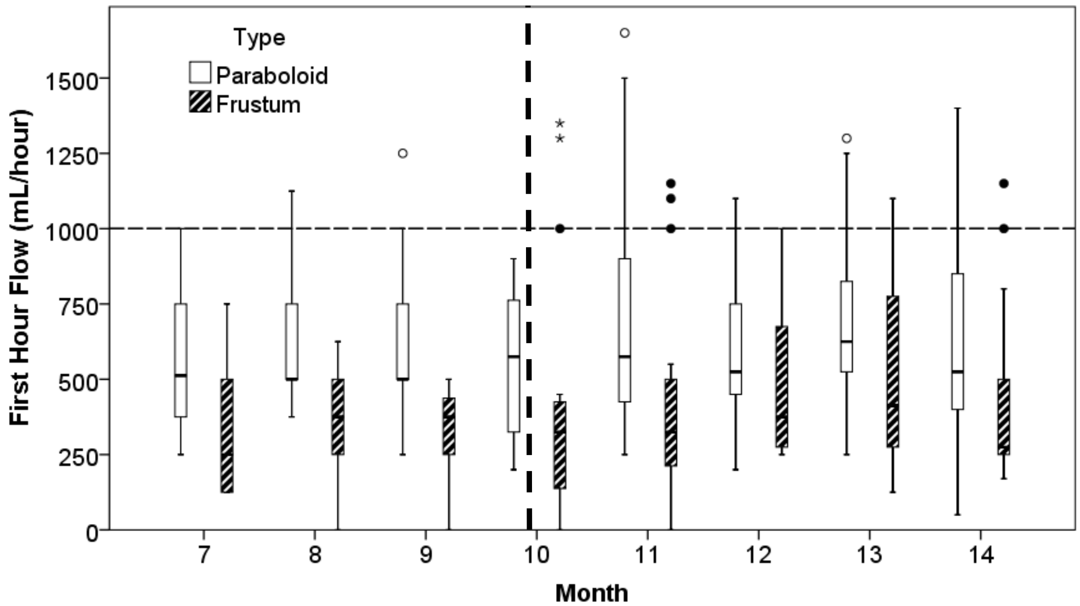


Figure 4-16 Average first hour flow rates for both filter types. The horizontal dashed line represents the minimum flow rate commonly used for quality control by filter manufacturers. Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.



Month	7	8	9	10	11	12	13	14
Sample Size								
Paraboloid	22	28	22	16	29	25	28	26
Frustum	20	23	15	16	19	12	12	14

Figure 4-17 First hour flow rate over the 47 weeks of the study. Data is shown in mL per hour for both filter types. The horizontal line represents the minimum acceptable flow rate used for quality control by filter manufacturers. The vertical dashed line divides the wet (7-10) and dry(11-14) months. Error bars represent the 95% confidence interval and the statistical outliers are shown as circles.

From the household surveys we know that, on average, households refilled their filters every 2.8 days (frustum) or 2.4 days (paraboloid). Given that the capacity for raw water of within the ceramic filter media upper reservoir (see Figure 4-2) is 8.5 liters for the frustum and 7.0 liters for the paraboloid, the average volume of water produced per day is 3 liters (frustum) and 2.9 liters (paraboloid). This volume would only be sufficient to meet the needs of households that have one person. Only one out of fifty-nine households in the community had one member (See Appendix R).

From Figure 4-16 we can see there is a significant difference in the performance of the two filter types, with the paraboloid filters having a higher flow rate. An independent samples t-test confirms that the difference in performance between the two filter types is statistically significant (p=0.000) when evaluating all measurements. When disaggregating by week, there was a statistically significant difference in average weekly flow rates between the paraboloid and frustum in 4 out of 8 weeks (p values less than 0.10). Looking at the filter performance over time there is a statistically significant difference in the values for the frustum filter between the wet and dry season. The frustum wet season average flow rate (362mL/hr.) was significantly different (p= 0.069) than the average dry season flow rate (452 mL/hr.). Although there was a statistically significant difference (p=0.004) in the average weekly raw water turbidity for the paraboloid filters in the wet season (represented by weeks 10 thru 38) compared to the dry season (represented by weeks: 47, 52, 56, and 59), no seasonal difference in flow rates for the paraboloid filters was observed. Flow rate did increase minimally for both filters over the course of the study. The average flow rate increased approximately 3% per week in the frustum filters; however the average increase was much less for the paraboloid filters (less than 0.3% per week). After 56 weeks the average flow rate was 495 and 642 mL per hour for the frustum and paraboloid filters respectively. Overall the performance for both filter types was significantly worse than the expectations outlined in the literature by both manufacturers.

4.7.5 Focus Groups and Household Surveys

Analyzing the comments made during the focus groups and the household surveys, the most commonly cited criticism was the filter flow rate, followed by the concern that the filtered water did not change the water flavor. The third most common concern was the fact that the filter lid did not fit correctly and that the tap could become contaminated easily. From the household survey conducted 10 months after filter distribution, 10 households had discontinued using the filters and another 6 filters were switched out because the flow rate was below 250 mL per hour, which was determined to be the minimum acceptable flow rate for this study. This means that over the first year the disuse rate was approximately 2.7% per month (16 filters out of 59 filters in 10 months) which is higher than that observed by Brown and colleagues (2009). It is also higher than a study that determined a decline in use of 20% after 9 months in Bolivia (Clasen et al. 2006).

Fifteen of sixteen women that participated in focus group reported using the filter, although two of the women had dry filters during the household visits the week prior. The one woman who admitted stopping using her filter cited a slow flow rate. Seven others (4 frustum and 3 paraboloid users) said that filtration rate of their filter was "very slow" and that they no longer filtered enough water for their household. As a result they were drinking unfiltered rainwater or tap water in addition to whatever their filter produced. Filtered water was only used for drinking, except in one case where a woman said that she infrequently bathed her infant with filtered water. Six out of sixteen women had children 5 years of age or younger, three of whom prepared formula or powdered milk with water for their children. Only two women had used filtered water to make formula, and both had boiled it prior to use, suggesting that they did not have confidence in the quality of the filtered water.

In general community members understood the connection between turbidity and water quality. Most women in the focus group and many respondents in the household surveys admitted adjusting their water consumption based on water source turbidity recognizing the danger in using river and spring water during or after rains as the turbidity increases. During these periods the women who use these sources switch to rainwater. One woman said she uses tap water only when the rainwater runs out. Several respondents admitted they had concerns about the quality of filtered water since it tasted the same as the raw water. One woman said "How can the filter work if it does not change the flavor of the water…it does not taste like bottled water." In the Dominican Republic 55.7 percent of the population relies on bottled water as their principal source of drinking water (ENDESA 2007). Ninety-eight percent of companies in 1993 used reverse osmosis processes to treat their water (Abreu 1996), which removes all ions and taste compounds, so that almost all bottled water tastes the same. Filtered water will not remove any ions in solution and so if spring water or surface water is used it will often have a different taste than bottled water, causing many users to be suspicious of the functionality of the filters.

The average price that women were willing to pay for a new filter was 337 RD (US$8.72) which is 72% of the actual price for the ceramic only and 35% of the complete unit. However there is the added cost of transport. Round trip transportation costs are 800 RD (US$21.62) to Moca which is the closest of the two filter factories. Only one of the 16 focus group participants said she would definitely be willing to purchase a replacement filter. With limited cash resources many women said that "they might have to spend money on something more important." The commercial availability of filters and the supply chain issues with obtaining replacement parts is a significant issue in determining the long term sustainability of point of use water treatment devices.

4.8 Conclusion

The data show that the CWFs in this study performed poorly with regard to water quality and hydraulic performance. Frustum filters removed only 29% of turbidity, while paraboloid filters removed 38%. In 22% of the samples the turbidity of the water collected from the tap was greater than the raw water turbidity, which is a significant concern as turbidity was highly correlated to microbial contamination, both E. coli and total coliform. Only 37% of the filtered water samples collected from the tap were free of microbial contamination, which is significantly lower than previous studies (Kallman et al. 2011). In addition, although it was not possible to calculate the percent or log removal due to difficulties quantifying the water quality of the raw water samples, it is clear that the percent of water samples falling into the Low to Intermediate Risk category is significantly lower in this study compared to other studies. These studies were performed on similar filter designs that were manufactured in different countries. The performance of CWF is highly dependent on the manufacturing variables such as materials, mix design, filter production, firing temperature, etc. A detailed discussion of these variables is provided elsewhere (Raynor 2009)

The majority of the filters performed below the manufacturer's specifications with regard to hydraulic efficiency. Only 17 filters out of the 59 filters that were distributed had measurements that were greater than 1,000mL/hr. Of the 327 first hour flow rate measurements taken in the field, only 34 individual flow rate measurements exceeded 1,000mL/hr. Baseline flow rates were not available to corroborate whether the initial flow rates met manufacturer's specifications. It is important to note that Filterpure does not use flow rate as a quality control measure and they claim that initially the filtration rate is low but will increase to 1.5 to 2 liters per hour as clay particles are washed out of the pores spaces. However, it is assumed that this process does not take more than a few weeks of regular use.

Focus groups and household surveys demonstrated that flow rate is a significant concern and may potentially affect the long term use of the filters. Although the implementation and training model used in this community was developed from materials provided by both filter manufacturers, it is likely that additional, and continual, follow-up training would be beneficial. The anecdotal findings of this research mirror findings of a report that stated that household water treatment products have not seen wide gains among lower income populations for the reasons that the supply does not meet consumer preferences related to convenience, aesthetics, taste, reliability, safety, and robustness (IFC, 2009).

4.8.1 Risk Factors to Sustainability

4.8.1.1 Competition from Bottled Water

The women all expressed concern of the high cost of bottled water, which is not sold in the community. A 5-gallon bottle costs 40 RD (37 RD = 1 USD) and a motorcycle taxi to the nearest vendor costs 60RD roundtrip. So theoretically, filters would have a significant cost savings over bottled water. However, bottled water has a long and established tradition providing water in the Dominican Republic. It is ubiquitously available throughout the country.

4.8.1.2 Commercial Availability

The availability of replacement filters and the supply chain issues of replacement parts is a concern for the sustainability of CWF. There are no filter distribution points and all filter purchases are done from the manufacturing facilities. Higuerito, where the paraboloid filters are manufactured, is 75 kilometers away (approximately 1 and a half hours in private car, 3 hours via public transportation). Yamasa, where the frustum filters are made, is 210 kilometers away, 3 hours in private vehicle or 5 hours in public transport. Via public transportation the trip will cost US$17 and $20 respectively. This doubles the cost of an individual filter.

In addition, the filter lids and spigots are currently not available in country and must be imported from China or the United States. Neither factory sells the lids or spigots individually, since they buy the units "as a package". This is a considerable risk factor to the sustainability of the filters

4.8.1.3 Quality Control and Regulatory Oversight

One possible reason for the poor performance of CWF in this study and other household water treatment products in general is the lack of sufficient oversight and accountability within this sector. In the United States, ceramic water filters with colloidal silver are regulated by the Environmental Protection Agency as the microorganisms targeted by the colloidal silver pathogen deactivation mechanism are legally defined as pests and hence subject to Environmental Protection Agency's Office of Pesticides Program (Lantagne 2001b). Organizations must register their product providing information on the toxicity and efficacy and pay a fee of US$1,000 per year to maintain the permit. Currently over 35 factories in 20 countries with production capacity of 37,700 filters per month are operating around the world (Raynor 2009). Many of these factories operate in less developed countries where the governments struggle with limited resources and regulatory capabilities. Average gross domestic product per capita for these countries (see Figure 4-1) is US$4,400 putting them in the poorest third of countries worldwide. This translates into little or no regulatory oversight of products marketed as point of use water treatment devices. Although instituting mandatory product testing would affect the final filter cost and hence marketability of the CWF, this cost is already borne by the user in the form of health care expenses from ineffective units.

Quality control in the manufacturing process is a likely a large determinant in the performance of the finished filter. Kallman et al. (2011) reported that only 40% of the fired filters passed the first hour flow rate test (1.0-2.5 liters/hour) used in the Guatemalan factory their study in 2008. This percentage improved to 80% by July 2009 with corresponding improvements in quality control (Kallman et al. 2011). Although many of the 26 field studies on CWF described the filter manufacturing process and stated that filters not meeting the acceptable range for flow rate testing are discarded, it is hard to believe that an organization could effectively function and destroy 20-60% of its product. At the very least this calls into question the financial sustainability of these factories. Furthermore there are ethical concerns associated with self-governance in the production of products that are marketed as health interventions.

Unfortunately the funding for monitoring and evaluation activities of water and sanitation schemes is limited and represents a small fraction of the total budget in this sector (Montgomery et al. 2009). Accountability is limited as systematic documentation of failed schemes or mechanisms to enforce consequences for investors who support poorly functioning or unsustainable programs often do not exist.

4.8.2 Future Research

Continued longitudinal studies of the long term in-situ performance of CWF are necessary. Such studies should be designed to include collecting water samples at different points (i.e. directly off the filter as well as from the spigot) and also systematically collecting information about user behaviors. This information will help determine what the impacts of different user behaviors are and also determine how important quality control is relative to user behavior. Field studies should be designed with the ultimate goal of providing information to filter manufacturers on how to improve their product and as well as the associated software (e.g. social marketing strategies, educational materials, implementation strategies). Future research should seek to determine if user acceptance rates are related to how well manufacturers integrate with the consumers of the filters. Controlled studies may look at long-term usage in areas where there is a demonstrated demand for point of use treatment technologies and where these technologies may already be commercially available compared to areas where CWF are not widely available.

Hydraulic performance of the filters in this study was significantly lower than the range required to meet the drinking water needs of households. The following chapter will discuss a mathematical model that can be used to improve the hydraulic performance of CWF.

5 WATER TREATMENT: HYDRAULIC MODELING OF CERAMIC WATER FILTERS[23]

5.1 Background

Despite enormous gains since 1990, about 780 million people worldwide still access their water from an unimproved source such as an unprotected spring, river, or dug well (UN, 2012). For these people, point-of-use treatment technologies are an important option to improve water quality and thereby reduce incidence of diarrhea or other waterborne diseases (Clasen et al. 2004; Fewtrell et al. 2005). One common point-of-use treatment option is the clay ceramic water filter (CWF) (Sobsey et al. 2008; Fry et al. 2013) which is now used in over 20 countries (Lantagne et al. 2010). A typical CWF is shaped like a bowl or a pot that can be nested within a storage receptacle. Users pour untreated water into the filter; under the influence of gravity, water flows through the porous structure of the filter, and filtrate is collected in the storage receptacle. An advantage of CWFs is that they can be produced using locally available materials (e.g. clay, sawdust, water).

Many previous studies of CWFs have focused on the extent to which they can improve water quality, particularly when the filters are coated or impregnated with silver to provide antimicrobial activity (Bielfeldt et al. 2009; Albert et al. 2010; Lantagne et al. 2010). CWFs can typically remove more than 99% of particles with a size (diameter) greater than 1 μm (Bielfeldt

[23] This chapter has been adapted with permission from Schweitzer, R.W., Cunningham, J.A., & Mihelcic, J.R. (2013) "Hydraulic Modeling of Clay Ceramic Water Filters for Point-of-Use Water Treatment." *Environ. Sci. Technol.* 47(1):429-35. doi: 10.1021/es302956f. Copyright 2013 American Chemical Society. See Appendix B for the copyright clearance letter from the publisher.

et al. 2010) and therefore have been observed to be effective at removing bacteria (Lantagne et al. 2010; Brown and Sobsey 2010; Murphy et al. 2010) although effectiveness decreases over time (Bielfeldt et al. 2009) These filters would also be expected to be effective at protecting against helminth eggs, protozoa, and protozoan cysts (van Halem et al. 2009) which typically have sizes of several microns or greater (Mihelcic et al. 2009). However, CWF removal of virus-size particles is highly variable (Bielfeldt et al. 2010) and therefore CWF protection against viruses is questionable (van Halem et al. 2009).

In addition to providing water of acceptable quality, CWFs must also meet other expectations of their users, including the expectation to provide water at an acceptable flow rate. In fact, one recent study found that flow rate may be the limiting factor in the user acceptance, functionality, and overall sustainability of CWFs (van Halem et al. 2009). Furthermore, specific improvements in public health have recently been estimated from incremental increases in water quantity through addition of a technological intervention (Fry et al. 2010). Adults may need 2–5 L/d of water for proper hydration, depending on climatic conditions and level of activity, and a typical family may require approximately 15 L/d (Howard and Bartram 2003; WHO 2006). Unfortunately, as discussed in Chapter 4 and as observed in additional field research on CWFs (Hwang 2003; Al-Moyed et al. 2008; van Halem et al. 2007), often water production has been insufficient to meet the basic water needs of the typical family. Therefore, to enable the continued usage of CWFs for point-of-use water treatment, we must be able to understand the factors that control the quantity of water produced, and to design CWFs to meet quantity expectations as well as quality expectations.

Three key parameters that can be used to quantify hydraulic performance of a CWF are the water level (h) in the filter, the instantaneous volumetric flow rate (Q) of filtrate, and the cumulative volume (*V*) of water produced by the filter since it was filled. These three metrics are all time-variant: as the filter drains, the water level in the filter drops, i.e. *h* decreases over time; concomitantly, the instantaneous flow rate *Q* decreases over time because of the reduction in hydraulic head; the volume produced, *V*, increases over time as more filtrate is collected in the storage receptacle. There have been some previous studies (though few in the peer-reviewed literature) that describe the hydraulic performance of CWFs, but these do not predict how $h(t)$, $Q(t)$, and $V(t)$ vary over time (Lantagne 2001a; Fahlin 2003; van Halem 2006; Miller 2010). Plappally and colleagues (2009) described the time dependence of $V(t)$ statistically but did not develop a physically based model for filter hydraulics (Plappally et al. 2009). Hence, there is no existing hydraulic model that is able to predict how $h(t)$, $Q(t)$, and $V(t)$ vary over time.

To address this knowledge gap, this chapter makes the following contributions. First, a mathematical model is presented that describes the hydraulic performance of ceramic water filters and is able to predict how water level (*h*), instantaneous flow rate (*Q*), and cumulative volume produced (*V*) vary over time (*t*). Second, two variants of the model are presented, corresponding to the two most common filter geometries: paraboloid-shaped and frustum-shaped. Third, both versions of the model are calibrated by comparison to experimental data. Fourth, the utility of the models is demonstrated by applying them to quantify the effects of user behavior and filter geometry on hydraulic performance. The capabilities of the models presented in this chapter could permit manufacturers to optimize filter geometry to maximize water production, and/or could allow implementing organizations to determine how changes in user behavior (e.g. the frequency of filling) will affect water production. Increasing water production will improve user satisfaction and, ultimately, the health of CWF users (van Halem et al. 2009; Fry et al. 2010).

5.2 Model Development

Filter performance, and hence the mathematical equations that describe it, depend on the geometry of the filter. Mathematical models applicable to the two most common geometries of ceramic pot filters are presented in the following sections. First is the paraboloid, or "bowl" geometry. Second is the frustum, also called a truncated circular cone, or the "flower pot" geometry. Photographs of both types are provided in Section 4.4 and schematic diagrams of paraboloid and frustum filters are shown in Figure 5-1.

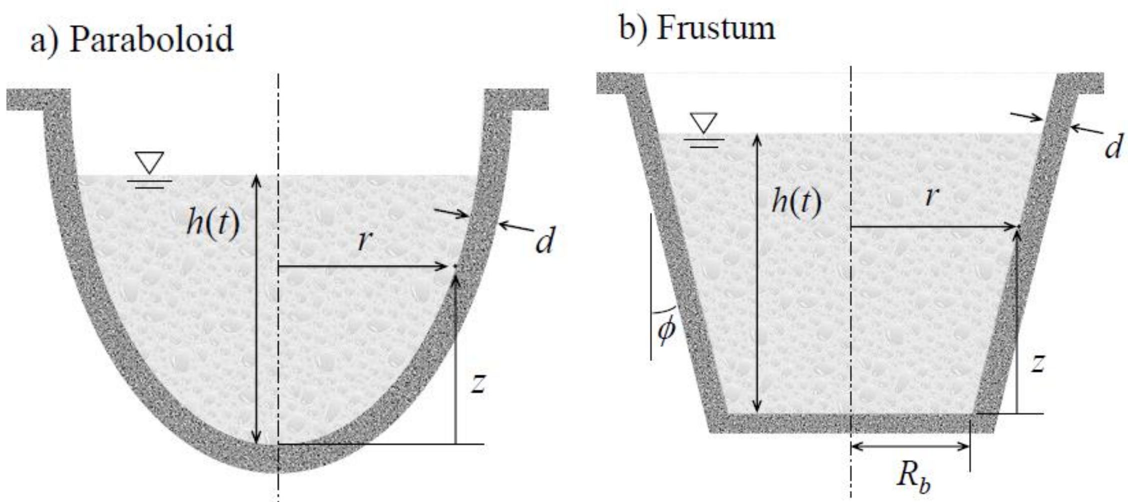


Figure 5-1 Schematic diagrams of the paraboloid and frustum filters

5.2.1 Paraboloid Filters

A schematic diagram of a paraboloid filter is provided in Figure 5-1a. The radius of the filter, *r*, increases with the height, z, from the bottom of the filter. To make the model general, we consider that the radius can be described by

$$r = a\, z^{n} \tag{5.1}$$

where *a* and *n* are parameters that describe the shape of the filter, and $0 < n < 1$ for a bowl with a concave shape. The most appropriate values of *a* and *n* can be determined for any individual filter by taking a few measurements as described subsequently. A low value of *n* means that the filter bowl is wide and rounded; a high value of n (close to 1) means that the filter is relatively narrow or "pointy." At any time t, the instantaneous volumetric flow rate $Q(t)$ is given by:

$$Q(t) = \iint_A q(z,t)\, dA = \int_0^{2\pi} \int_0^{h(t)} q(z,t)\, r\, dz\, d\theta \tag{5.2}$$

where $q(z, t)$ is the specific discharge through any point on the filter surface. From Darcy's law, we know that the specific discharge is given by:

$$q(z,t) = K \frac{h(t) - z}{d} \tag{5.3}$$

where K is the hydraulic conductivity of the filter material, $h(t)$ is the water level in the filter, and d is the thickness of the filter. In this chapter, we assume that K and d are uniform in space and constant in time; future versions of the model may account for factors such as clogging (decrease of K over time) or filter walls that are thicker in some parts of the filter than others (dependence of K on z). Substituting equations (5.1) and (5.3) into (5.2) yields the following.

$$Q(t) = \frac{2\pi\, K\, a}{d} \int_0^{h(t)} \left[h(t) - z\right] z^n\, dz = \frac{2\pi\, K\, a}{d\,(n+1)(n+2)} \left[h(t)\right]^{n+2} \tag{5.4}$$

We know from a mass balance of the water in the filter that

$$\frac{dV(t)}{dt} = Q(t) \tag{5.5}$$

but, from the geometry of the filter, we also know that

$$\frac{dV(t)}{dt} = -\pi \left[r_h(t)\right]^2 \frac{dh(t)}{dt} \tag{5.6}$$

as the filter drains, where $r_h(t)$ is the filter radius that corresponds to the water level $h(t)$. Combining equations (5.1), (5.4), (5.5), and (5.6), we arrive at a differential equation that describes how the water level in the filter is expected to decrease over time.

$$\frac{dh(t)}{dt} = -\frac{2\, K}{a\, d\,(n+1)(n+2)} \left[h(t)\right]^{2-n} \tag{5.7}$$

This differential equation has the following solution:

$$h(t) = \left[h_0^{\,n-1} + \frac{2\,K\,(1-n)\,t}{a\,d\,(n+1)(n+2)} \right]^{\frac{1}{n-1}} \tag{5.8}$$

where h_0 is the initial water level in the filter pot at time $t = 0$. By combining equation (5.8) with equation (5.4), we arrive at an expression for how the instantaneous volumetric flow rate, $Q(t)$, varies as a function of time.

$$Q(t) = \frac{2\pi\,K\,a}{d\,(n+1)(n+2)} \left[h_0^{\,n-1} + \frac{2\,K\,(1-n)\,t}{a\,d\,(n+1)(n+2)} \right]^{\frac{n+2}{n-1}} \tag{5.9}$$

Finally, when the water level is h, we know that the volume of water remaining in the filter, $V^{remaining}(t)$, is given by:

$$V^{\,remaining}(t) = \frac{\pi [r_h(t)]^2\, h(t)}{2n+1} \tag{5.10}$$

which implies that the initial volume of water in the filter is given by the following:

$$V^{\,initial} = \frac{\pi r_0^{\,2}\, h_0}{2n+1} \tag{5.11}$$

where r_0 is the radius of the paraboloid filter that corresponds to the initial water level h_0. Since the cumulative volume of water produced by the filter, $V(t)$, must be equal to $V^{initial} - V^{remaining}(t)$, we can derive the following expression for $V(t)$.

$$V(t) = \frac{\pi\, r_0^{\,2}\, h_0}{2n+1} \left\{ 1 - \left[1 + \frac{2\,K\,(1-n)\,h_0\,t}{(n+1)\,(n+2)\,d\,r_0} \right]^{\frac{2n+1}{n-1}} \right\} \tag{5.12}$$

Equations (5.8), (5.9), and (5.12) provide closed-form analytical mathematical expressions for $h(t)$, $Q(t)$, and $V(t)$ for the paraboloid-shaped filter. The number of parameters describing the system can be reduced markedly by working in terms of non-dimensional variables. We define the following non-dimensional variables:

$$\bar{t} = \frac{2\,(1-n)\,h_0\;K\,t}{(n+1)\,(n+2)\,d\;r_0} \qquad \bar{h} = \frac{h}{h_0}$$

$$\bar{Q} = \frac{Q\,d\;(n+1)\,(n+2)}{2\pi\;K\,r_0\;h_0^{\;2}} \qquad \bar{V} = \frac{V\;(2n+1)}{\pi\,r_0^{\;2}\;h_0} \tag{5.13}$$

which then allows the dimensional equations (5.8), (5.9), and (5.12) to be written in the following simple forms.

$$\bar{h}(\bar{t}) = \left(1+\bar{t}\right)^{\frac{1}{n-1}} \tag{5.14}$$

$$\bar{Q}(\bar{t}) = \left(1+\bar{t}\right)^{\frac{n+2}{n-1}} \tag{5.15}$$

$$\bar{V}(\bar{t}) = 1-\left(1+\bar{t}\right)^{\frac{2n+1}{n-1}} \tag{5.16}$$

It is interesting to note that in the non-dimensional forms of the equations, *n* is the only dimensionless parameter that appears in the equations. By specifying *n*, the behavior of the system is known.

5.2.2 Frustum Filters

A schematic diagram of a frustum filter is provided in Figure 5-1b. The filter contains a flat, circular bottom of radius R_b. Sides of the filter are slanted from perpendicular at an angle *Φ*, as shown in Figure 5-1b, such that the radius of the filter, *r*, at any height *z* can be given by the following.

$$r = R_b + z\tan\phi \tag{5.17}$$

Values of R_b and Φ are easy to measure for any particular frustum-shaped filter. For the purposes of this chapter, we assume that the hydraulic conductivity, K, and the filter thickness, d, are the same for the bottom of the filter and the sides of the filter, i.e. $K_{bottom} = K_{sides} = K$.

The instantaneous volumetric flow rate $Q(t)$ is given by the sum of the flow through the flat bottom and the flow through the slanted sides: $Q(t) = Q_{bottom}(t) + Q_{sides}(t)$. Thus

$$Q(t) = \pi R_b^{\,2} q_{\text{bottom}}(t) + \iint_{A_{sides}} q(z,t)\, dA \tag{5.18}$$

where $q_{bottom}(t)$ is the specific discharge through the bottom of the filter, and $q(z, t)$ is the specific discharge through any point on the side of the filter. Making use of equation (5.3),

$$Q(t) = \frac{\pi R_b^{\,2}\; K\, h(t)}{d} + \int_0^{2\pi}\int_0^{h(t)} K\, \frac{h(t) - z}{d}\, r\, dz\, d\theta \tag{5.20}$$

where for simplicity we have assumed that the hydraulic conductivity K and the thickness d are the same for the bottom of the filter as they are for the sides. Equation (5.20) is similar to an equation given in Table 2.15 of van Halem (2006). Then, substituting (5.17) into (5.20) and integrating provides the following.

$$Q(t) = \frac{\pi\, K\, h(t)}{d}\left\{ R_b^{\,2} + R_b\; h(t) + \frac{1}{3}\tan\phi\,\left[h(t)\right]^2 \right\} \tag{5.21}$$

Equation (5.21) is equivalent to equation (7-8) of Miller (2010) and can also be compared to equation (2.8) of van Halem (2006). By combining equations (5.5), (5.6), (5.17), and (5.21), we derive the differential equation that describes how the water level, $h(t)$, varies in time.

$$\frac{dh(t)}{dt} = -\frac{K\, h(t)}{d}\; \frac{\frac{1}{3}\tan\phi\left[h(t)\right]^2 + R_b\; h(t) + R_b^{\,2}}{\tan^2\phi\left[h(t)\right]^2 + 2\, R_b\, \tan\phi\, h(t) + R_b^{\,2}} \tag{5.22}$$

Equation (5.22) is the frustum analog to equation (5.7), which was derived for the paraboloid filter geometry. However, unlike equation (5.7), equation (5.22) cannot be integrated analytically. It must be solved numerically. This is easy to do in a program like Matlab® or Excel® using an explicit Euler routine to integrate from the initial condition, $h(t) = h_0$ at time t = 0, to any desired time t.

The instantaneous flow rate, $Q(t)$, can be determined at any desired time t by solving equation (5.22) for $h(t)$, and then using equation (5.21) to solve for $Q(t)$. The cumulative volume of water produced, $V(t)$, can be computed from equation (5.23).

$$V(t) = \pi R_b^{\,2}\left[h_0 - h(t)\right] + \pi\, R_b\, \tan\phi \left\{h_0^{\,2} - \left[h(t)\right]^2\right\} + \frac{\pi}{3}\tan^2\phi \left\{h_0^{\,3} - \left[h(t)\right]^3\right\} \tag{5.23}$$

Equations (5.22), (5.21), and (5.23) provide equations for $h(t)$, $Q(t)$, and $V(t)$ for the frustum-shaped ceramic filters.

For the frustum geometry, non-dimensional variables can be defined as follows.

$$\bar{t} = \frac{k\,t}{d} \qquad \bar{R}_b = \frac{R_b}{h_0} \qquad \bar{h}(\bar{t}) = \frac{h(t)}{h_0}$$

$$\bar{Q}(\bar{t}) = \frac{Q(t)\,d}{\pi\,K\,h_0\left(R_b^{\,2} + R_b\,h_0 + \frac{1}{3}\tan\phi\,h_0^{\,2}\right)}$$

$$\bar{V}(\bar{t}) = \frac{V(t)}{\pi\,h_0\left(R_b^{\,2} + R_b h_0\,\tan\phi + \frac{1}{3}h_0^{\,2}\tan^2\phi\right)} \tag{5.24}$$

This allows us to present dimensionless forms of equations (5.21)–(5.23).

$$\frac{d\bar{h}(\bar{t})}{d\bar{t}} = -\bar{h}(\bar{t})\frac{\bar{R}_b^{\,2} + \bar{R}_b\,\bar{h}(\bar{t}) + \frac{1}{3}\tan\phi\left[\bar{h}(\bar{t})\right]^2}{\bar{R}_b^{\,2} + 2\,\bar{R}_b\,\tan\phi\,\bar{h}(\bar{t}) + \tan^2\phi\left[\bar{h}(\bar{t})\right]^2} \tag{5.25}$$

$$\bar{Q}(\bar{t}) = \frac{\bar{R}_b^{\,2}\,\bar{h}(\bar{t}) + \bar{R}_b\left[\bar{h}(\bar{t})\right]^2 + \frac{1}{3}\tan\phi\left[\bar{h}(\bar{t})\right]^3}{\bar{R}_b^{\,2} + \bar{R}_b + \frac{1}{3}\tan\phi} \tag{5.26}$$

$$\bar{V}(\bar{t}) = \frac{\bar{R}_b^{\,2}\left[1-\bar{h}(\bar{t})\right] + \bar{R}_b \tan\phi \left\{1-\left[\bar{h}(\bar{t})\right]^2\right\} + \frac{1}{3}\tan^2\phi \left\{1-\left[\bar{h}(\bar{t})\right]^3\right\}}{\bar{R}_b^{\,2} + \bar{R}_b \tan\phi + \frac{1}{3}\tan^2\phi} \tag{5.27}$$

5.3 Model Calibration and Evaluation

To calibrate the mathematical models developed in the previous sections, we performed falling-head tests on two representative filters: one frustum (obtained from Potters for Peace) and one paraboloid (obtained from FilterPure), manufactured at different factories in the Dominican Republic. For more details on the production processes of these filters see Chapter 4 or Appendix L. Details of the two specific filters used in the research in this chapter are provided in the following sections.

5.3.1 Filter Geometry

The geometric properties of the filters were measured and are summarized in Table 5-1. The filter thicknesses, *d*, for both the paraboloid filter and the frustum filter were estimated by measuring the filter thicknesses at multiple locations with an outside caliper and then taking arithmetic averages. The current versions of the model approximate *d* as spatially uniform; future versions of the models may account for *d* varying with height (in the case of the paraboloid), or for differences between the bottom thickness and the sidewall thickness (in the case of the frustum). The initial water depth, h_0, was measured for both filters with a device described in Appendix V. For the paraboloid, the shape parameters *a* and *n* were determined by measuring the filter radius, *r*, at six different values of *z*, and then fitting Equation (5.1) to the measured data (R^2 = 0.993). For the frustum, R_b and Φ were measured using a steel tape measure and adjustable drafting triangle, respectively. Additional details about measurement procedures are provided in the Appendix V.

Table 5-1 Geometric properties of two filter shapes used in laboratory research.

Filter Shape	Parameter	Value
Paraboloid	d	1.92 cm
	a	3.8353 $cm^{0.6508}$
	n	0.3492
	h_0	23.0 cm
	r_0	11.5 cm
Frustum	d	1.42 cm
	R_b	9.75 cm
	Φ	9.5°
	h_0	21.1 cm

5.3.2 Falling Head Tests

Falling-head tests were performed as follows. First, the filters were saturated with tap water for 36 hours prior to testing, following accepted procedures (Nederstigt et al. 2005). Then, each filter was filled with tap water (20°C), and the initial water depth h_0 was measured as noted above. The filters were allowed to drain as in normal operation, and filtrate was collected. At regular time intervals (1, 2, 3, 4, 5, 8, 12, 16, 22, and 28 hr.), the water level $h(t)$ in the filter was measured and recorded, and the volume of filtrate produced since the previous measurement was also measured and recorded. Measurements of $h(t)$ are estimated to be accurate to within ±0.1 cm; measurements of volume are estimated to be accurate to ±5 mL.

The maximum hydraulic gradient during the falling-head test occurs at the start of the test and is equal to h_0/d. Table 5-1 gives values of h_0 and d for both filters. From these we estimate maximum hydraulic gradients of approximately 12 cm/cm for the paraboloid and 15 cm/cm for the frustum. As the filters drain, the hydraulic head decreases, and therefore so does the hydraulic gradient across the filter.

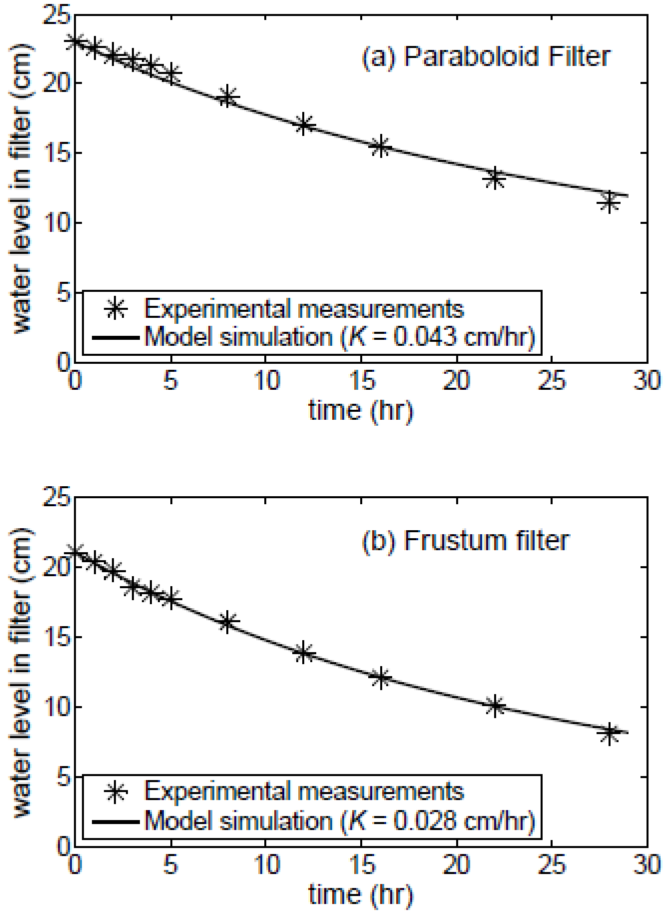


Figure 5-2 Comparison of laboratory measured water levels to model simulations. Graph shows values for the paraboloid-shaped filter (top) and the frustum-shaped filter (bottom). Values of hydraulic conductivity, K, were selected to minimize error between observations and model simulations. Values were 0.043 cm/hr. (1.2×10–7 m/s) for the paraboloid and 0.028 cm/hr. (0.78×10–7 m/s) for the frustum shape

5.3.3 Estimates of Hydraulic Conductivity

The hydraulic models were applied to simulate the collected $h(t)$ data from the falling-head tests. Equation (5.8) was applied to the paraboloid data, and equation (5.22) was solved numerically and applied to the frustum data. All parameters in equations (5.8) and (5.22) were estimated *a priori* (as described in Section 5.3.1) except for the hydraulic conductivity, K. The hydraulic conductivity for each filter was estimated by finding the value of K that minimized the error (i.e. sum of the squares of the differences) between the measurements and the model predictions. Each filter had ten measurements of $h(t)$ at the times noted above, and each data point was weighted equally in estimating *K*. Results of the calibrated models are compared to the experimental data in Figure 5-2. Estimates of *K* were 0.043 cm/hr. (1.2×10^{-7} m/s) for the paraboloid and 0.028 cm/hr. (0.78×10^{-7} m/s) for the frustum.

5.3.4 Model Evaluation

From Figure 5-2, it appears that the hydraulic models perform well for both filter types in simulating the experimental data as long as the hydraulic conductivity, *K*, can be treated as an adjustable parameter. The average relative error between data points and model predictions was 2.4% for the paraboloid and 1.1% for the frustum. Also, model predictions of the cumulative volume of filtrate produced, $V(t)$, agree well with measured values (comparison provided in Appendix W). Furthermore, the estimated values of *K* (0.043 cm/hr. = 1.2×10^{-7} m/s, 0.028 cm/hr. = 0.78×10^{-7} m/s) appear reasonable when compared to previous estimates in the literature. For instance, Oyanedel-Craver and Smith (2008) reported values of *K* in the range 0.041–0.18 cm/hr. (1.15×10^{-7} – 5.01×10^{-7} m/s) for three filters manufactured with natural soils and commercial pottery clay. Similarly, van Halem and co-workers tested filters from three countries with similar results: Cambodia 0.046 cm/hr. (1.3×10^{-7} m/s), Ghana 0.048 cm/hr. (1.3×10^{-7} m/s), and Nicaragua 0.017 cm/hr. (0.047×10^{-7} m/s) (van Halem et al. 2007). The good agreement between measurements and simulations, along with the reasonable estimates of *K*, build confidence that the models are adequately describing the hydraulics of both the paraboloid filter and the frustum filter.

5.4 Model Application

Water production from CWFs is a function of water characteristics (e.g. turbidity, temperature), user behavior (e.g. frequency of filling or cleaning), and filter properties (e.g. geometry, materials, mix ratio). To demonstrate the utility of the models presented here, they are applied to quantify how user behavior and filter geometry affect the hydraulics. The following two questions are answered. First, how much additional water can be produced by filling the filter more frequently? Second, how does the volume of water produced depend upon the shape of the filter?

5.4.1 Effect of Frequency of Filling

After a filter is filled, the rate at which filtrate is produced (i.e. $Q(t)$) decreases over time, because the hydraulic head in the filter decreases as the filter drains, as does the area of the filter through which flow is occurring. Re-filling the filter to its original water depth increases the hydraulic head, the wetted surface area, and the water flux to their original values (if there is no clogging over time). Therefore, increasing the frequency with which the filter is re-filled may increase the volume of water produced in any given time period. However, from a practical standpoint, there are limits to how often users are willing to re-fill their filters. We therefore limited our consideration to three scenarios: filters are filled once per day, filters are filled twice per day (every 12 hours), or filters are filled three times per day (every 8 hours).

By applying the hydraulic model, we are able to quantify how much additional water is yielded by more frequent re-filling. For model simulations, we used the filter properties from our two test filters, i.e. the properties listed in Table 5-1 along with the estimates of K from our falling-head tests. Equations (5.12) and (5.23) can be used to estimate the volume of water produced by the filters. For the "base case" of filling once per day, equations (5.12) and (5.23) can be used without modification. For the case of filling twice per day, equations (5.12) and (5.23) can be used to simulate the first 12 hr. of performance, but for $t > 12$, one must use $V(t) = V(12) + V(t–12)$ to account for the re-fill at the 12-hr point. A similar procedure was used to estimate $V(t)$ for the three-fills-per-day scenario. For $8 < t < 16$, $V(t) = V(8) + V(t–8)$. For $t > 16$, $V(t) = V(16) + V(t–16)$.

Results are shown in Figure 5-3. For the paraboloid filter, the model predicts that filling once per day produces 3.43 L/d (consistent with the results of our falling-head test, which yielded 3.57 L in 22 hr.). Filling twice per day increases the output to 4.53 L/d, a 32% increase; filling three times per day increases the output to 5.04 L/d, a 47% increase over the baseline. Similar results were obtained for the frustum. The model predicts that filling once per day produces 5.30 L/d (consistent with our falling-head test, which yielded 5.02 L in 22 hr.). Filling twice per day increases the output to 6.95 L/d, a 31% increase; filling three times per day increases the output to 7.71 L/d, a 45% increase.

These model results suggest that a significant gain in water production may be easy to achieve for some CWF users. For instance, if a user currently collects approximately 8 L (2 gal) of unimproved water once per day, then merely by re-filling the filter to its maximum capacity three times per day, the user may achieve a gain of ~45% in the volume of water produced. This may be significant in improving the health of household members. This finding represents one example of the type of analysis that is facilitated by the hydraulic models presented here.

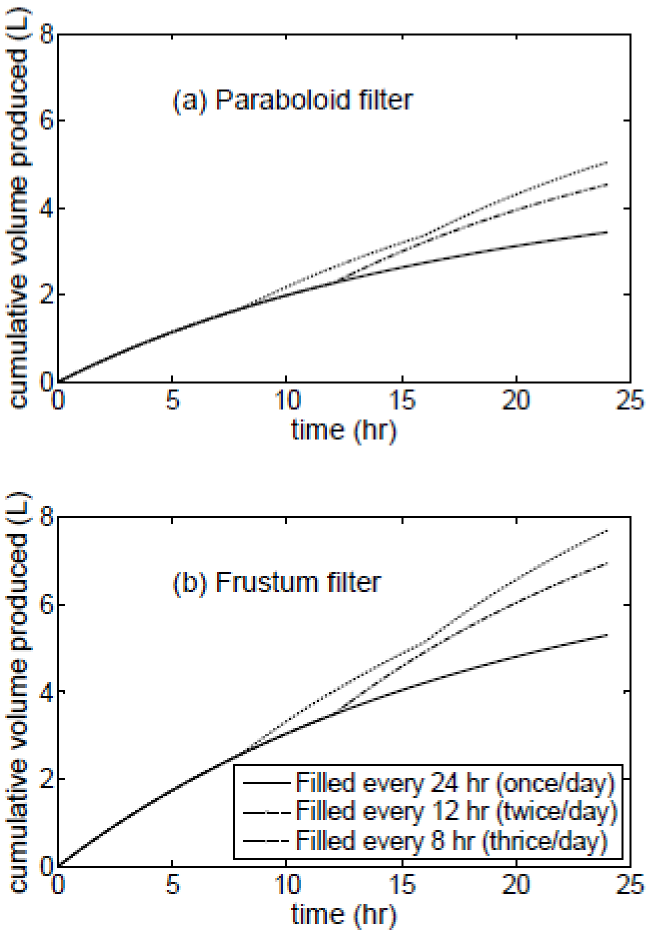


Figure 5-3 Model predictions of cumulative water volume and filling frequency. Values are shown if filters are re-filled once per day (every 24 hr.), twice per day (every 12 hr.), or three times per day (every 8 hr.). For both filter geometries, re-filling every 8 hr. increases water production by about 45% as compared to re-filling every 24 hr.

Furthermore, this particular finding may be especially important, because many current users of CWFs apparently do not frequently re-fill their filters to maximize water production. A study of 506 households in Cambodia found that users reported filling their filter an average of 1.8 times per day; this suggests that many households in the study were probably filling their filter only once per day (Brown et al. 2009). Another study reported that, in Nicaragua, over 30% of households filled their filters once per day or less (Walsh 2000), and a third study reported that 3 of 22 households only re-filled the filters after they were completely empty (Lantagne 2001b). Therefore, the models developed here may represent a tool that can demonstrate quantitative improvements accompanying a specific change in user behavior, which would likely be useful to promoters of ceramic water filters.

5.4.2 Effects of Filter Geometry

To further demonstrate the utility of the hydraulic model, we apply the model to quantify how filter geometry affects water production. We compare the predicted amount of water produced from two hypothetical paraboloid filters that have slightly different shapes: one is tall and thin, the other is shallow and wide. The tall, thin paraboloid has an initial water depth h_0 = 30.9 cm and has shape parameters a = 2.157 cm$^{0.50}$ and n = 0.50. The shallow, wide paraboloid has an initial water depth h_0 = 23.2 cm and has shape parameters a = 5.467 cm$^{0.75}$ and n = 0.25. The two filters are otherwise similar: both have the same hydraulic conductivity (K = 0.030 cm/hr. = 0.83×10^{-7} m/s), the same filter thickness (d = 2.0 cm), the same radius at the top of the filter (r_0 = 12.0 cm), and the same initial volume of water (7.00 L). (It is possible to show, for the paraboloid filter, that the initial volume of water is given by $V^{\text{initial}} = \pi\ h_0\ (r_0)^2/(1+2n)$.) Therefore, the only significant difference between these two hypothetical filters is the difference in their shapes. Also, both filters are based on realistic values of capacity, hydraulic conductivity, and thickness.

Equation (5.4) is applied to both of these hypothetical filters to predict how much water is produced in a 24-hr period, assuming that the filters are filled only once. The results are shown in Figure 5-4. The model simulations predict that the tall, thin filter can produce about 4.11 L/d, versus only 3.27 L/d for the shallow, wide filter – an increase of about 25%. The gain comes from the fact that, even though the two filters have the same overall capacity, the taller filter operates under a larger hydraulic head, and therefore experiences a higher flux.

This result suggests one way in which filter design can perhaps be optimized to produce higher flow rates. Taller filters produce more water than shorter ones, all other things being equal. Currently, the geometry of CWFs is often based on the limits of the storage receptacles in which the filters are nested. Five-gallon (20-L) plastic buckets are a commonly used storage receptacle as they are inexpensive and readily available. Furthermore, these buckets provide sufficient storage capacity below the bottom of the inserted filter, such that the water level in the bucket does not typically reach the bottom of the filter (which would slow or stop further drainage through the filter). However, if filter manufacturers are seeking ways to increase filter output, then altering the shape and exploring alternative storage receptacles may be a practical solution. Plastic containers in various sizes are becoming more readily available as plastic manufacturing expands in developing countries (Andrady and Neal 2009). Understanding the effects of filter geometry on hydraulics represents a second example of the type of analysis that is facilitated by the hydraulic models presented here.

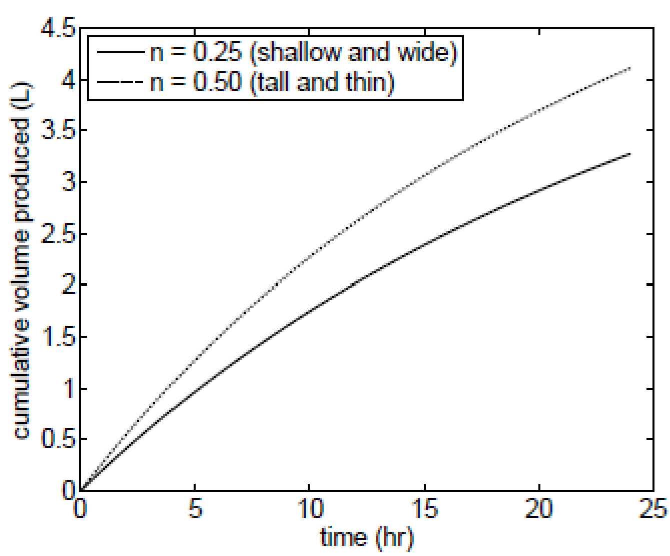


Figure 5-4 Model predictions of cumulative water volume for two paraboloid designs. Figure shows V(t) for two paraboloid filters with slightly different shapes. The tall and thin filter (*n* = 0.50) produces water faster than the shallow and wide filter (*n*=0.25) even though both filters have the same hydraulic conductivity (*K*= 0.030 cm/hr. = 0.83x10^{-7} m/s), same wall thickness (*d*=2.0 cm), and same overall capacity (7.0L).

5.5 Model Considerations and Future Research Directions

The current versions of the hydraulic models have some issues that need to be considered in future versions and are discussed in more detail below. Despite these issues, the hydraulic models presented here can serve as important tools for filter manufacturers to improve their design, and/or for filter users to derive maximum benefit. The models presented here are, to the best of our knowledge, the first mathematical models capable of predicting how water level, instantaneous filtrate flow rate, and cumulative water production vary over time during use of a ceramic water filter. Future work will be aimed at accounting for the key factors, discussed below, that have not yet been incorporated into the model.

5.5.1 Spatial Variability of Filter Properties

The filter thickness d is treated as spatially uniform, even though our measurements indicated the thickness of the filter bottom may be as much as 50% different from the thickness of the side walls. Similarly, the hydraulic conductivity K is treated as spatially uniform; e.g. for the frustum, the hydraulic conductivity of the bottom is assumed equal to that of the sides. However, previous experiments demonstrated the hydraulic conductivity varied along the wall of paraboloid filters (Miller 2010) and similar conclusions have been observed for frustum filters (Lantagne et al. 2010). Future versions of the hydraulic models could be modified to account for spatial variations in wall thickness and/or hydraulic conductivity. Spatial heterogeneity is a factor in many applications of porous media, and sometimes necessitates progression from analytical models to numerical models. In the case of ceramic filters, analytical models may be able to effectively account for such heterogeneity. Unlike the soil matrix in groundwater science, porous ceramic is a manufactured material, and therefore the properties can more easily be controlled. Significant efforts are being made to improve manufacturing processes and reduce material heterogeneity (Raynor 2009). Furthermore, the good agreement between experimental data and the current versions of the models shows that using a single "effective" thickness and conductivity does not prevent the models from accurately describing filter hydraulics.

5.5.2 Estimating Hydraulic Conductivity

The current versions of the models require the hydraulic conductivity, *K*, to be treated as an adjustable or "fitting" parameter. Ideally, the models would use a priori estimates of K to eliminate the need for data fitting. However, it is likely very difficult to a priori estimate *K*, because filter construction is likely to vary greatly from one factory to another, and perhaps even between individual filters from a single factory. Unless more stringent quality control measures are implemented, it may be unavoidable that *K* must be estimated individually for each filter whose performance is of interest. What is desirable, then, is a simple and rapid test that can accurately estimate *K*, preferably in a time frame shorter than the 28 hr. required for the falling-head tests reported here. For instance, it may be that a constant-head permeability test, in which the filters are kept full during testing, would be able to yield an accurate but more rapid estimate of *K*. This hypothesis will be tested in a future study.

5.5.3 Effect of Turbidity and Filter Clogging Over Time

It would generally be expected that more turbid water would filter more slowly than less turbid water, because the higher particulate loading would more rapidly clog some of the filter pores. Also, as the turbidity leads to filter clogging, it would be expected that the hydraulic performance of the filter would decline over time (van Halem et al. 2007; van Halem et al.

2009). The current versions of the hydraulic models do not account for the effect of turbidity on hydraulic performance, nor for the change in hydraulic performance over time.

Several previous studies have investigated how turbidity and other water-quality parameters affect filter hydraulics and filter clogging over time (Ragusa et al. 1994; Pavelic et al. 2007; Siefert and Engesgaard 2012). These studies quantify the rates and effects of clogging due to both physical factors (i.e. decrease in filter porosity as particles accumulate in filter pore spaces) and biological factors (i.e. growth of biofilms or biological colonies that alter filter hydraulics). However, to the best of our knowledge, most or all previous work pertains to granular-media filters or membrane filters, and there has not yet been an investigation into the effects of turbidity on the hydraulics of CWFs. Phenomenological filtration models, as reviewed elsewhere (Crittenden et al. 2005; Iritani et al. 2007) may be applicable to CWFs. However, for CWFs, the situation may be more complicated because the presence of colloidal silver on the inside surface or in the CWF microstructure affects microbial growth (Lantagne et al. 2010; Bielefeldt et al. 2010; Brown and Sobsey 2010; Kallman et al. 2011, Mwabi et al. 2012) and because the leaching of silver nanoparticles over time may also affect filter hydraulics. Therefore, a quantitative description of how turbidity affects filter hydraulics is left for future work.

It is worth noting that, in the field, source waters with high levels of turbidity (i.e. > 30 NTU) are recommended to be pre-treated. Established sedimentation and filtration methods for pre-treatment include the three-pot treatment system or locally produced cloth and paper filters (Mihelcic et al. 2009). Therefore, it is not likely that CWFs would be used to treat highly turbid waters without pre-treatment. In addition, CWF manufacturers have methods for “cleaning” the filter that are provided to a user in training when filters are sold or distributed.

5.5.4 Other Filter Configurations

This chapter has focused on only two filter geometries, both of which are based on the same general filter configuration (see Figure 5-1), and were used in the field research component in the Dominican Republic (see Chapter 4). Other ceramic filter configurations that are not manufactured from clay, such as the "candle" filter, are widely used in some locations (Chaudhuri et al. 1994; Clasen and Menon 2007). The candle filters are typically made from a synthetic ceramic, which, as noted elsewhere, requires high-purity raw materials and an industrial manufacturing process, often resulting in a more expensive filter (Oyanedel-Craver and Smith 2008). Therefore, this chapter considered only the filter configurations that are typically made locally with locally available materials, like the ones manufactured in the Dominican Republic and studied in Chapter 4. However, the same general approach applied here is applicable to candle filters, and perhaps to other filter configurations as well (e.g. the "tulip" filter). These extensions are left for future research.

6 CONCLUSION

Significant progress has been made with regard to the Millennium Development Goal Target 7c, to halve the population without sustainable access to safe drinking water and basic sanitation by 2015. The goal for drinking water, achieving 88% coverage to an improved source, has been reached ahead of the 2015 deadline; however there is evidence that the sustainability of a significant proportion of the water supply infrastructure in developing countries is questionable (Sara and Katz 1996; Harvey and Reed 2006; IRC 2009). In addition, progress reducing the population without access to basic sanitation, currently at 37% without coverage, is well behind the 2015 target of 25%. Lack of access to an improved water source or basic sanitation and hygiene services and/or declining levels of service from existing water, sanitation, and hygiene (WASH) infrastructure can lead to negative impacts on health. Furthermore, disaggregating the WASH monitoring data it is clear that there are inequities with regard to coverage and how improvements in WASH services have been experienced by different demographics (e.g. poor, rural inhabitants, disabled, other marginalized groups). It is therefore important to ensure the appropriate management of water WASH infrastructure.

Understanding the current global status of WASH, this research focuses on the water sector. The objective of this research is to identify the critical factors affecting the management of water supply and treatment at the community or household level, with an emphasis on rural and peri-urban areas in the developing world. Chapter 1 provided background information on the status of water and sanitation coverage worldwide and also an overview of the different management models that are used in the provision of water supply services.

6.1 Water Supply Management

In rural areas low population density, limited cash economies, and geographical isolation are challenges facing providers of water supply services. As a result community management is often the default water supply service delivery model utilized. The Sustainability Assessment Tool developed in Chapter 2 of this dissertation serves as a diagnostic to inform decision-making, characterize specific needs of rural communities in the management of their water supply systems, and identify weaknesses in training regimes or support mechanisms. The tool is composed of fifteen specific measures which result in a score of sustainability likely (SL), possible, or unlikely for eight indicators. A weighting factor is applied to each indicator to provide an overall sustainability score. The framework was tested on 61 statistically representative geographically stratified sample communities with rural water supply systems in the Dominican Republic. Twenty-three percent of systems were assessed to be SL, 59% sustainability possible, and for 18% it is unlikely the community will be able to overcome a significant challenge(s). As support from an outside agency increased so did community participation ($p = 0.005$) and financial durability ($p = 0.004$). Increased accounting transparency was correlated to increased compliance with user tariffs ($p < 0.001$) and system age was inversely correlated to management transparency ($p = 0.003$) and community activity level ($p = 0.005$).

The findings demonstrate the importance of long-term involvement by outside groups to support community management activities. This has significant implications when developing budgets and accounting for the total life cycle costs of providing water supply services. The ultimate goal of this Sustainability Assessment Tool and other similar monitoring frameworks is to inform decision making and provide information for long term strategic planning and budgeting.

Research has shown that long-term costs of water supply service delivery may be higher than previously assumed (Gibson 2010). Chapter 3 presents a framework, developed by the IRC-International Water and Sanitation Centre, for identifying the costs of providing water, sanitation and hygiene (WASH) services to rural and peri-urban communities in developing countries. When using this life-cycle cost approach, often detailed and disaggregated information about household expenditures on water services is not available. The data from developing countries is usually limited to financial expenditures and is often based on self-reported aggregate expenditures on water from private water vendors. The existing studies of economic expenditures on water are from medium to large-sized cities and have been focused on piped household connections.

Chapter 3 analyzes the financial and economic expenditures on water services in 9 rural and peri-urban communities in three different regions in Burkina Faso, West Africa. The data were collected as a part of the WASHCost life-cycle costing project. Households were categorized as Non-poor (NP), Poor (P), or Very Poor (VP) using a qualitative participatory method. Service levels were identified following WASHCost methods and benchmarks used by the Burkinan Government. Field data are from a general household survey (7,399 households), water point survey (86 water points), and two detailed household surveys conducted in the dry (492 households) and wet (518 households) seasons.

Average capital expenditures on water were US$6.73 per person and both recurrent financial and economic expenditures ranged between US$7 and US$9 per person per year. Very few households reported making any capital maintenance contribution. The cumulative expenditure on water for the average household was US$16.62 per person per year. Rural households had lower annual pecuniary expenditures (by US$17-18 per household per year) but higher annual economic expenditures (by US$28 per household per year) than urban households of the same size. In the dry season household financial costs increased by approximately 32% (US$1.40 per household per month), while the opportunity costs increased by 55% (US$1.65 per household per month). One additional person in the household resulted in a per person savings of approximately US$0.60 in capital expenditures but higher annual household pecuniary costs of US$5 per household per year, economic costs of approximately US$1.25 per household per year, and cumulative costs of US$6.75 per household per year.

Absolute financial and economic expenditures on water did not vary between different socio-economic groups, however expenditures on water relative to total household expenditures were greater in the very poor households. The very poor spent more compared to other households: 9% in financial terms, 11% in economic terms, and 30% cummulatively when controlling for the effects of season , household size, and rural-urban differences. In addition, the average financial expenditures in water as a per cent of household income for all socio-economic categories in this research (18%) was well above the affordability threshold of 5% which is used by World Bank and other organizations. Furthermore, households that use a handpump as their primary source spend an average of US$5.50 per person per year, which is significantly greater than the affordability target of the Burkina government (US$0.50 per person per year).

The analyses presented in Chapter 3 demonstrate that there are serious considerations with regard to the affordability of water services in Burkina Faso and the need to improve subsidy targeting in the water sector. This research supports the inclusion of affordability and equity indicators into the framework for measuring access to improved water supply services. Understanding the affordability of these services and the comprehensive life-cycle costs are in an important and necessary step in ensuring sustainable service delivery

The tools and analyses presented in Chapters 2 and 3 are crucial for making the shift away from a “projectized” approach to water supply and WASH in general, whereby projects are conducted in isolation and insufficient planning is made to account for the demands (whether technical, financial, managerial, institutional, etc.) to ensure the service provided can continue over the long-term. The shift from “project” thinking to “service” thinking is important. A service delivery approach is a conceptual approach taken at the sector level to the provision of WASH services which emphasizes the entire life-cycle of a service, both the hardware and software requirements to provide services at a very specific level with regard to specified indicators, (e.g. water quality, quantity, accessibility, reliability, etc.).

If the management of water supply infrastructure at the community level is not adequate and service levels begin to deteriorate, in order to sustain the health benefits, it may be necessary to manage water quality on the household level. Chapters 4 and 5 of this research addressed the issues surrounding the management of water treatment using household level technologies.

6.2 Managing Water Treatment

For the over 780 million people who access their water from an unimproved source such as an unprotected spring, surface water, or dug well, point-of-use water treatment technologies are an important option to improve water quality and reduce the risk of water related diseases. These technologies allow households to access water sources that would otherwise be unacceptable (e.g. shallow groundwater via handpumps in urban areas) and they can serve as insurance against highly variable water quality in systems with intermittent service (e.g. piped water in urban areas with low electricity reliability). Point-of-use technologies can also allow the household to take responsibility of the management of water quality, where management at the community level might otherwise be unreliable. In addition, effective infrastructure management is not a sufficient condition for ensuring water quality and eliminating health risks to consumers. Field studies have demonstrated that water quality from improved sources can deteriorate significantly after collection, while in transit to the household, and within the household prior to consumption (Gundry et al. 2006). As a result water treatment technologies implemented and managed at the household level and combined with safe storage practices are proposed as a means of reducing the risk of water contamination from the source to the household or within the household prior to consumption.

There are a wide variety of point-of-use technologies that implore different mechanisms to treat the water. One common point-of use treatment option is the clay ceramic water filter (CWF). The principal materials necessary to manufacture CWF: clay, saw dust, and water, are available in many developing countries and therefore they has been widely manufactured and promoted. However, research has diverged on whether CWF and other POU technologies are universally applicable and should be widely promoted.

Laboratory research has been very optimistic about the microbial treatment capacity of CWF, with demonstrated removal abilities reaching several log removal (Bielfeldt et al. 2009; Bielfeldt et al. 2010; Lantagne et al. 2010). Field studies, however, have demonstrated a less optimistic capacity of CWF, with an average of 76% and 55% of filtered water samples meeting World Health Organization guidelines (i.e. 0 CFUs per 100mL sample) from cross-sectional and longitudinal studies respectively. As a result of the conflicting data between laboratory and field research and amongst field studies, a study was performed to evaluate the long-term in-situ performance of two different commercially available ceramic water filters in a rural community in the Dominican Republic. One design included in this study, manufactured by FilterPure, was a paraboloid-shaped that has colloidal silver mixed in with the filter raw materials prior to firing. The second design, manufactured by IDEAC, is the frustum-shaped filter promoted by Potters for Peace. For this filter, the silver was applied by painting on a mixture of colloidal silver and water after the ceramic was fired.

Fifty-nine households received CWF, with thirty randomly selected to receive paraboloid-shaped filters and the balance receiving frustum filters. Data collection included user focus groups, household surveys and measurements of filter flow rate and water quality. The data collected over fourteen months demonstrates that the CWFs in this study performed poorly with regard to filtrate water quality and hydraulic performance. Frustum filters removed only 29% of turbidity, while paraboloid filters removed 38%. In 22% of the samples the turbidity of the water collected from the tap was greater than the raw water turbidity, which is a significant concern as turbidity was highly correlated to microbial contamination, both E. coli and total coliform. Only 37% of the filtered water samples collected from the tap were free of microbial contamination, which is significantly lower than previous studies (Dundon 2009; Kallman et al. 2011). Fifty-six percent of water samples collected in this study qualified as Low to Intermediate Risk compared with 75% of the longitudinal studies in the reviewed literature. Weekly variation in filtered water quality was significant, suggesting the filters in this study are unreliable means of treating water to acceptable levels.

In addition, the majority of the filters performed below the manufacturer's specifications with regard to hydraulic efficiency. Only 17 filters out of the 59 filters that were distributed had measurements that were greater than 1,000 mL/hr., the quality control metric used by many CWF manufacturers. Paraboloid filters had higher flow rates on average as compared to frustum filters. Focus groups and household surveys demonstrated that flow rate is a significant concern and may potential affect the long term use of the filters.

Previous research determined that user perception of flow may be equally as important as the actual measured flow rate in the uptake of filter (du Preez et al. 2008). The research presented in Chapter 4 supports the findings of a report that stated that household water treatment products have not seen wide gains among lower income populations for the reasons that the these technologies often do not meet consumer preferences related to convenience, aesthetics, taste, reliability, safety, and robustness (IFC, 2009). To enable the continued usage of CWFs for point-of-use water treatment, filter manufacturers must be able to understand the factors that control the quantity of water produced, and to design CWFs to meet quantity expectations as well as quality expectations. Therefore Chapter 5 presents mathematical models that can be used to predict the hydraulic performance of CWFs.

The acceptability of ceramic filters for point-of-use water treatment depends not only on the quality of the filtered water, but also on the quantity of water the filters can produce. In Chapter 5 two mathematical models for the hydraulic performance of ceramic water filters under typical usage are developed. A model is developed for the most common filter geometries: paraboloid- and frustum-shaped. Both models are calibrated and evaluated by comparison to experimental data. The hydraulic models are able to predict the following parameters as functions of time: water level in the filter (h), instantaneous volumetric flow rate of filtrate (Q), and cumulative volume of water produced (V). The models' utility is demonstrated by applying them to estimate how the volume of water produced depends on factors such as the filter shape and the frequency of filling. Both models predict that the volume of water produced can be increased by about 45% if users refill the filter three times per day versus only once per day. This information would be beneficial for social marketing campaigns and promotional materials targeting filter users. Ease of use and convenience will likely ensure that continued use of household level water treatment technologies. The models developed predict that filter geometry affects the volume of water produced: for two filters with equal volume, equal wall thickness, and equal hydraulic conductivity, a filter that is tall and thin will produce as much as 25% more water than one which is shallow and wide. These models can be used as tools to help optimize filter performance.

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APPENDICES

Appendix A List of Acronyms

CAPEX	capital expenditure
CAPMANEX	capital maintenance expenditure
CDC	Centers for Disease Control
CESDEM	República Dominicana Encuesta Demográfica y de Salud (Dominican National Health and Demographic Survey)
CFA	Communauté Financière d'Afrique franc (West African franc, monetary code XOF)
CFU	coliform forming units
CWF	ceramic water filter
ENDESA	Encuesta Demográfica y de Salud (Dominican National Health and Demographic Survey)
EPA	Environmental Protection Agency
FLOW	Field level operations and maintenance
GDP	gross domestic product
GIS	geographic information system
HH Dry	household surveys conducted during the dry season
HH Wet	household surveys conducted during the wet season
ICAITI	Central American Industrial Technology Institute
IDEAC	Instituto de Desarrollo de la Economía Asociativa
IDWSSD	International Drinking Water Supply and Sanitation Decade
INAPA	Instituto Nacional de Aguas Potables y Alcantarillado (National Water and Sanitation Authority)
JMP	Joint Monitoring Programme
lpcd	liters per capita per day
LRV	log removal value
MDG	Millennium Development Goal
MF	membrane filtration
MIPC	Masters International Peace Corps program
MPN	most probable number
NGO	non-government organization
NP	Non-poor household
NSF	National Science Foundation
NTU	nephelometric turbidity units
ONE	Oficina Nacional de Estadisticas (National Statistics Office)
ONEA	Office National de l'Eau et de l'Assainissement (National Office for Water and Sanitation)
OPEX	operations expenditure
$OPEX_{ECON}$	economic operations expenditure
P	Poor household
POU	point of use treatment technologies
SEM-EDS	Scanning Electron Microscope
SL	sustainability likely
SP	sustainability possible
SU	sustainability unlikely

Appendix A (Continued)

UN	United Nations
UNICEF	United Nations Children's Fund
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
US$	United States dollars (currency)
UV	ultraviolent
VP	Very Poor household
WASH	water, sanitation, and hygiene
WHO	World Health Organization
WtPt1	preferred water point (WtPt2, second preferred water point, etc.)

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Title: Hydraulic Modeling of Clay Ceramic Water Filters for Point-of-Use Water Treatment

Author: Ryan W. Schweitzer, Jeffrey A. Cunningham, and James R. Mihelcic

Publication: Environmental Science & Technology

Publisher: American Chemical Society

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Figure B-2 Copyright clearance letter for the manuscript that Chapter 4 is based on.

Appendix C Summary of Select Variables

Table C-1 Summary of select variables used in Chapter 3

Variable	Units	Definition
Variables normalized per person		
CAPEX	$/person	Capital expenditures (Includes money, labor and materials)
CAPMANEX	$/person/year	Capital maintenance expenditure (Includes money, labor and materials)
OPEX1	$/person/year	Annual financial operating expenditures (yearly estimates) per person
OPEX2* (aka OPEXfin)	$/person/year	Annual financial operating expenditures (daily estimates) per person
Financial_EX	$/person/year	Total financial expenditure on water per person per year
OPEXeconA	$/person/year	Economic expenditures (opportunity costs) calculated using empirical data to determine transportation mode carrying capacity.
OPEXeconB (aka OPEXecon)	$/person/year	Economic expenditures (opportunity costs) calculated using field observations to determine transportation mode carrying capacity.
Cumm_EX	$/person/year	Cumulative expenditure (financial and economic) on water per person per year using dry season (8 months) and wet season (4 months) data.
Rev_EX	$/person/year	Total household income normalized per person per year
Exp_EX	$/person/year	Total expenditure on all goods and services per person per year
water_use	Liters/person/day	Per person daily water consumption
Variables normalized by Household		
OPEX2_TOT	$/household/year	Annual financial operating expenditures (daily estimates) per household
Financial_TOT	$/household/year	total financial expenditure on water per household per year
OPEXeconB_TOT*	$/household/year	Household annual economic expenditures (opportunity costs) calculated using field observations to determine transportation mode carrying capacity.
Cumm_TOT	$/household/year	Minimum expenditure (financial and economic) on water per household per year
Rev_TOT	$/household/year	Total annual household revenue
Exp_TOT	$/household/year	Total annual household expenditures
HH_size	# people/household	Number of members in each household
HH_water_use	Liters/household/day	Total household daily water consumption
Miscellaneous Variables		
Collxn_time	Minutes/day	Minutes per day dedicated to collecting water for each household
Wtpt1_dist	Meters	Distance to first prefferred water point (wtpt2 is second point, etc)
Wtpt1_trips	# trips	Number of trips from the water point to the household for transporting containers.

Appendix D Focus Group Discussion

Table D-1 Focus group discussion summary notes

		Very Poor (VP)	Poor (P)	Non-poor (NP)
Rural	Aorema	Insufficient food or clothing for all members of household.	No other income generating activities other than agricultural	One that can meet their needs and also those of others, with livestock or working in the trade.
Rural	Bouere	Insufficient food to eat; Shelter of poor quality; No/poor quality shoes; No/poor quality clothes; No mat in home; No groundnuts or millet; 0.5 hectares or less	Less than 3 meals per day; Does not have crops after October; 2 ha cotton, 1 ha corn, 1 ha millet; Takes seed and money on loan;	Able to eat all year and has no problems if crops fail; Durable housing and has a motorcycle or other motor vehicle; 15 to 20 ha of cotton and 3-4 pairs of oxen yoked or tractors.
Rural	Dossi	Insufficient food to eat; Shelter of poor quality; No/poor quality shoes and clothes; 0.5 ha sorghum or millet, No corn; Cannot afford fertilizer; No plough or oxen	Can meet their needs but has none left to help family or friends; It can operate 5ha composed of 2ha cotton 1ha but 1ha white sorghum and red sorghum 1 ha; Up to two oxen	Whoever gets to take charge, who can help others and comes to realize all these projects. Operates 10-30 ha, composed of 15ha cotton 10ha but 3ha of white sorghum, red sorghum 1ha, 0.5 ha and 0.5 ha groundnut cowpea. It has at least five pairs of oxen or a tractor.
Rural	Komsilga	Insufficient food to eat; Shelter of poor quality; No/poor quality shoes; No/poor quality clothes	Can feed and clothe themselves; A means of transport (bike); Less than 5,000 CFA in bank; Educates children with difficulty.	Three meals a day; Durable house.; Educates children with ease; Has motor vehicle.
Rural	Margo	Insufficient food to eat	Can meet their needs but has none left to help family or friends.	Has sufficient millet and can help others; Has invested in cattle and the village.
Rural	Yagma	A single coat; No shoes; Cannot meet basic food requirement without help; No animals, No transportation; Simple shelter.	Has at most two chickens and one goat or sheep, eat no more than twice a day, house of 10 sheets or mud hut has a bicycle as a means of travel.	Has sufficient food ; Has cattle; Well-dressed; Motor vehicle; Educated children; Large house /Durable materials
Peri-Urban Sectors	1	Insufficient food to eat; Requires external assistance to survive	Can meet their needs but has none left to help family or friends	Whoever gets to meet his basic needs and can help others.
Peri-Urban Sectors	2	Physical disability; Needs assistance to meet basic needs	Can meet their basic needs but may not eat 3 times a day. Willing to work but may not have means.	Has something at the end of the month and eat three times a day.
Peri-Urban Sectors	30	House can be built in 3 days.; Cannot afford rice; Precarious housing; Insufficient dishes; Difficulty covering costs of schooling for children; Unemployed/No income; Must sell sand or gravel.	A person who can manage to ensure its daily meal; Has a flat of millet or maize; A limited purchasing power	Able to afford a bag of millet, who dresses well; Brick house; A good means of transport; That can be treated; Which can provide three meals; Who may have access to education

Appendix E Economic Expenditure Assumptions

The following list describes the assumptions used to calculate the economic expenditures on water collection in the survey communities in Burkina Faso.

1. One-way distance in meters from household to source (d_N) was obtained from GIS data from all communities except Sector 1 in Ouahigouya. Therefore, Sector 1 was excluded from the analysis for OPEXecon and cummulative expenditures.

2. Average queue time (t_N) was determined for each individual water point from the water point surveys. Although queue time may vary between days of the week or hours of the day previous observations have shown that these differences are not significant and will normalize over the course of the year (Mu et al. 1990).

3. Speed of travel (v) is assumed to be that of the slowest mode of travel. Various modes of travel were observed at the Burkin Faso study locations: walking, bicycle, donkey, wheelbarrel, handcart, donkey carriage and motorized vehicle (motorcycle, car,tractor, etc). For the human and animal driven modes, literature suggests that the transportation speeds are similar (Pushpangadu 2001; Wickler et al. 2000; Maloly et al. 1986). Only a small percentge of households, less than 3 per cent, used motor vehicles to transport water and field observations determined that any time savings through these modes of transport were partially offset by the time to load/unload containers. Also, there is the difficult issue of accounting for the additional costs for the operation and maintenance of motorized vehicles, which can vary by orders of magnitude. Furthermore, the savings achieved by motor vehicles, bicycles, or animals can be accounted for in the differential carrying capacity (volume per trip) of each method. Considering these issues and the general range of values available in the literature, a standard speed of 55

Appendix E (Continued)

meters/minute was used to obtain estimates of collection times from distance data for all modes of travel.

4. Number of trips (r_N) was calculated using the total volume of water collected and the volume of water that can be carried per trip (see equation E.1). The water volume is a function of the carrying capacity of each individual mode of travel. The carrying capacity was estimated using 1) empirical data from the water point surveys (describted below as Method A) and 2) through a second "practical" method (described below as Method B).

$$r_N = \frac{Total\ Volume}{Volume\ per\ trip} \tag{E.1}$$

Method A for Determining Carrying Capacity: Based on observations from the water point surveys, this method utilizes the self-reported daily total water volume collected by each household and divides it by the average volume of water carried per trip per mode of travel. The values for the maximum and average volume of water transported per trip by each of the travel modes is provided in Table E-1. Due to the large standard deviation of these values and the assumption that users will utilize the full capacity of each container (verses an average value) an alternative method (i.e. Method B) was explored.

Table E-1 Carrying capacities of travel modes observed in Burkina Faso

Travel Mode	Average Volume (liters/trip)	Max volume (liters/trip)	Std Dev (liters/trip)
Walking	37	280	37
Bicycle	43	1,200	43
Hand cart	119	660	70
Beast (no cart)	175	660	162
Wheel barrel	218	1,540	72
Animal cart	240	640	127
Other	70	1,800	154

Appendix E (Continued)

Method B for Determining Carrying Capacity: The total number of trips required to transport water containers back to the household can be determined by knowing the mode of travel and the total number of containers used to collect water at each of the preferred water sources, assuming that containers were filled to capacity prior to transport. This, however, requires knowledge of the transportation capacity (i.e. number of containers) of each mode of travel. The values for transport capacity of different travel modes, is based upon the field experience of the author and was confirmed by observation by field personnel in Burkina Faso, are provided in Table E-2.

Table E-2 Container transportation capacities for different travel modes in Burkina Faso

Travel Mode	220L Barrel (L)	20L Jerry-can (J)	15L Basin (N)	10L Bucket (T)	Combinations
Walking	0	1	1	2	1N 1T
Bicycle	0	2	1	2	1J 1T
Hand cart	1	6	1	8	1L1J;1L1N; Any combo of J and T up to 6
Beast (no cart)	0	2	0	2	1J1T
Wheel barrel	1	3	1	2	2J1T, 1J2T
Animal cart	2	10	4	14	1L2N;1L5J;1L7T;5J2N; 5J7T; 2N7T
Other	2	10	4	14	Same as animal cart

Note: For a given mode of travel the total number of each type of container that could be transported per trip is listed for Barrels (L), Jerry-cans (J), Basins (N), and Buckets (T). The last column labelled "Combinations" lists possible combinations of containers that may be carried per trip. For example, with a wheel barrel it is possible to carry 3 jerry cans or 2 buckets. It is also possible to carry, with a wheel barrel, 2 jerry cans and a bucket or 1 jerry can and 2 buckets.

5. Value of time (*v*) can be calculated in many ways. A detailed discussion of different methods used in the determination of the costs of water collection is available elsewhere (Nauges and Whittington, 2009). However, among the only authors to provide empirical evidence about the pecuniary costs of collecting water from non-tap sources were Whittington et al. (1990). They determined, in one of the few water demand estimation studies

conducted in Sub-Saharan Africa (and the only study performed in a small town) that the value of time for households relying on non-household water sources was greater than previously estimated and likely equal to that for unskilled labor in some cases (Whittington et al.,1990). The minimum daily wage rate for unskilled labor in Burkina Faso is 162.37 CFA (US$ 0.32) per hour. The Inter American Development Bank uses a more conservative value, 50 per cent of the market wage rate for unskilled labor (i.e. 81 CFA per hour), as the valuation of time based upon transportation research in the developing world. However, for this research the value of time was derived from household surveys conducted in the dry season using the annual household income (Rev_TOT). The hourly value of time was calculated as follows assuming an 8 hour work day, 240 work days a year:

$$v = \frac{(Rev\_TOT / HH\ size)}{1920\ hours/year} \tag{E.2}$$

The mean and median value of time for each socio-economic class is shown in Table E-3. This table shows that the value of time used in Burkina Faso are more conservative than opportunity cost calculations procedures used elsewhere (e.g. Hutton and Haller, 2004; Whittington et al. 1990).

Table E-3 Value of time used to calculate opportunity costs in Burkina Faso. (Data Source: HH Dry)

	Sample Size (household)	Mean (CFA/hour)	Median (CFA/hour)
Non-poor	178	79.8	34.7
Poor	232	46.8	23.0
Very Poor	82	27.5	16.5
All	493	55.6	24.3

Appendix F Correlation Analysis Results

The life-cycle cost categories (CAPEX, CAPMANEX, $OPEX_{FIN}$, $OPEX_{ECON}$) as well as total financial expenditure (Financial_EX) and cumulative expenditure (Cumm_EX) were compared to other continuous variables using SPSS version 20.1 (Armonk, New York). Sample size (n), Pearson Product statistics, and the statistical significance (95 and 99 per cent are indicated with asterisks) are presented in Table F-1. The columns of Table F-1 are labelled A through O and the rows are numbered 1 through 15 so that results can be referenced[24]. This table contains results for the dry and wet season surveys. For cost categories involving GIS data (e.g. water point distance and opportunity costs) Sector 1 data was excluded from the analysis (columns J through O and rows 10 through 15).

[24] Output tables from bivariate correlations are symmetric about the diagonal axis. So for example, the values from the correlation between "HH size" and "Cumm_EX" are shown in A15 and O1.

Appendix F (Continued)

Table F-1 Correlation analysis results. Sector 1 data excluded from columns J thru O and rows 10 thru 15.

			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
			HH_size	water use	HH water use	Rev_TOT	Exp_TOT	CAPEX	CAPMANEX	OPEXfin	Financial_EX	wtpt1_dist	wtpt2_dist	wtpt1_trip	wtpt2_trip	OPEXecon	Cumm_EX
1	size_hh	r	1	-.284**	.363**	.060	.152**	-0.030	-.123**	-.116**	-.149**	.007	-.036	.230**	.201**	-.257**	-.293**
		N	968	968	968	878	878	878	878	968	878	774	178	815	288	758	702
2	water use	r	-.284**	1	.648**	.106**	.104**	0.037	.217**	.369**	.385**	-.045	.155*	.148**	.047	.283**	.348**
		N	968	968	968	878	878	878	878	968	878	774	178	815	288	758	702
3	HH water use	r	.363**	.648**	1	.149**	.217**	.005	.058	.272**	.257**	-.040	.060	.343**	.263**	.000	.079*
		N	968	968	968	878	878	878	878	968	878	774	178	815	288	758	702
4	Rev_TOT	r	.060	.106**	.149**	1	.322**	.119**	.026	.078*	.080*	-.143**	-.137	-.066	-.088	.296**	.273**
		N	878	878	878	878	878	878	878	878	878	719	165	757	269	757	702
5	Exp_TOT	r	.152**	.104**	.217**	.322**	1	0.057	.136**	.038	.067*	-.131**	-.087	-.068	-.022	0.032	.078*
		N	878	878	878	878	878	878	878	878	878	719	165	757	269	757	702
6	CAPEX	r	-0.030	0.037	0.005	.119**	0.057	1	-0.009	0.019	0.017	-0.020	-0.043	-0.044	-0.060	0.017	.075*
		N	878	878	878	878	878	878	878	878	878	719	165	757	269	757	702
7	CAPMANEX	r	-.123**	.217**	.058	.026	.136**	-.009	1	.075*	.295**	-.019	0.088	.007	.014	.127**	.482**
		N	878	878	878	878	878	878	878	878	878	719	165	757	269	757	702
8	OPEXfin	r	-.116**	.369**	.272**	.078*	.038	0.019	.075*	1	.975**	-.123**	-.066	.044	.286**	.121**	.376**
		N	968	968	968	878	878	878	878	968	878	774	178	815	288	758	702
9	Financial_EX	r	-.149**	.385**	.257**	.080*	.067*	0.017	.295**	.975**	1	-.120**	-.070	.038	.284**	.144**	.469**
		N	878	878	878	878	878	878	878	878	878	719	165	757	269	757	702
10	wtpt1_dist	r	.007	-.045	-.040	-.143**	-.131**	-0.02	-.019	-.123**	-.120**	1	.489**	.105**	.026	.142**	0.020
		N	774	774	774	719	719	719	719	774	719	774	166	774	276	720	664
11	wtpt2_dist	r	-.036	.155*	.060	-.137	-.087	-.043	0.088	-.066	-.070	.489**	1	.103	-.043	0.078	-0.018
		N	178	178	178	165	165	165	165	178	165	166	178	178	175	165	147
12	wtpt1_trips	r	.230**	.148**	.343**	-.066	-.068	-0.044	.007	.044	.038	.105**	.103	1	.501**	0.061	.012
		N	815	815	815	757	757	757	757	815	757	774	178	815	288	758	702
13	wtpt2_trips	r	.201**	.047	.263**	-.088	-.022	-.060	.014	.286**	.284**	.026	-.043	.501**	1	-0.036	0.079
		N	288	288	288	269	269	269	269	288	269	276	175	288	288	270	242
14	OPEXecon	r	-.257**	.283**	.000	.296**	0.032	.017	.127**	.121**	.144**	.142**	0.078	0.061	-0.036	1	.624**
		N	758	758	758	757	757	757	757	758	757	720	165	758	270	758	702
15	Cumm_EX	r	-.293**	.348**	.079*	.273**	.078*	.075*	.482**	.376**	.469**	0.020	-0.018	.012	0.079	.624**	1
		N	702	702	702	702	702	702	702	702	702	664	147	702	242	702	702

Pearson (r)	Strength
$0.5 \leq r$	large
$0.3 \leq r < 0.5$	medium
$0.1 \leq r$ 0.3	small
$r < 0.1$	no correlation

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix G Ordinal Regression Analysis Results

Unlike linear regression models the results of ordinal regression do not describe the magnitude of the effect between the independent model parameters (or variables) and the dependent model outcome. The quantitative effects in linear regression are the beta values (β). Ordinal regression models are only able to describe the nature (positive or negative) of relationships and the statistical significance or each relationship. This significance is described by the p-value, which if less than 0.05 is considered to be statistically significant. The ordinal regression models are shown below. The strength of the models is described by rho squared (ρ^2). The following tables describe the effects of different variables on water quality monitoring (Table G-1 and G-2) and accessibility (Table G-3 and G-4) of the primary and secondary water points as well as overall service levels (Table G-5).

Table G-1 Effects on water quality monitoring of primary water source (ρ^2=0.319). Sector 1 data was excluded from the model. Only statistically significant parameters are shown. Data missing for at least one of the parameters for 60 households

Parameter	Estimate	Std. Error	p-value
Quality = No Service	-6.753	.497	0.000
Quality = Basic	-2.791	.469	0.000
Quality = High	---	---	---
Financial_EX	6.040E-05	1.651E-05	.000
OPEXeconB	3.546E-06	1.193E-05	.766
collxn_time_wtpt1	-.012	.002	.000
Rural	-4.128	.470	.000
dry	.537	.212	.011

Table G-2 Effects on water quality monitoring of secondary water source (ρ^2=0.056). Sector 1 data was excluded from the model. Only statistically significant parameters are shown. Data missing for at least one of the parameters for 60 households.

Parameter	Estimate	Std. Error	p-value
Quality = No Service	2.336	.189	0.000
Quality = Basic	3.462	.220	0.000
Quality = High	---	---	---
Financial_EX	2.836E-05	1.049E-05	.007
OPEXecon	2.212E-05	8.089E-06	.006
Dry	.921	.195	.000
Non-poor	.588	.187	.002

Appendix G (Continued)

Table G-3 Effects on accessibility crowding at the primary water source (ρ^2=0.021). Sector 1 data was excluded from the model. Only statistically significant parameters are shown. Data missing for at least one of the parameters for 95 households.

Parameter	Estimate	Std. Error	p-value
Crowding = Sub-standard	-.664	.143	0.000
Crowding =Basic	---	---	---
Financial_EX	3.621E-05	1.479E-05	.014
OPEXeconB	-2.959E-05	1.066E-05	.005
vol_wtpt1	-.001	.001	.020
collxn_time_wtpt1B_per_person	.023	.007	.002
ave_time_wtpt1	.033	.009	.000

Table G-4 Effects on accessibility crowding at the secondary water source (ρ^2=0.056). Sector 1 data was excluded from the model. Only statistically significant parameters are shown. Data missing for at least one of the parameters for 118 households.

Parameter	Estimate	Std. Error	p-value
Crowding = Sub Standard	1.871	0.214	0.000
Crowding =Basic	---	---	---
OPEXeconB	2.074E-05	8.555E-06	.015
Financial_EX	2.789E-05	1.071E-05	.009
Dry	.913	.195	.000
NP	.566	.187	.003

Table G-5 Effects on overall service level (ρ^2=0.017). Sector 1 data was excluded from the model. Only statistically significant parameters are shown. Data missing for at least one of the parameters for 58 households.

Parameter	Estimate	Std. Error	p-value
Overall_service = No Service	-.739	.165	.000
Overall_service = Sub-Standard	.998	.166	.000
Overall_service = Basic	2.072	.184	.000
Overall_service = Intermediate	5.695	.604	.000
Overall_service = High	---	---	---
Rural	-.382	.152	.012
Financial_TOT	5.132E-06	1.134E-06	.000
OPEXeconB_TOT	-9.838E-07	1.353E-06	.467
Dry	.085	.135	.529
VP	.430	.173	.013

Appendix H Silver in Ceramic Water Filters

Silver has a long history of use as a biocide in food storage, bandages, and other medical products (Chen and Schluesener 2008). Silver has the capability to deactivate many water borne pathogens (Lok et al. 2007; Dubas et al. 2006). It has been suggested this capability relies on a number of different mechanisms including: adhesion to the cell wall altering surface membrane properties (Sondi and Salopek-Sondi, 2004), penetrating cell and damaging DNA, and dissolving into its reactive state (Ag^+) which can enhance microbial properties by reacting with proteins (Matsumura et al. 2003) or it can increase effectiveness of other toxic mechanisms such as UV inactivation (Kim et al. 2008). This motivated CWF manufacturers to incorporate silver into their product.

In a controlled laboratory environment CWF treated with silver has shown the ability to increase the quality of effluent water (Lantagne 2001a; Oyanadel-Craver and Smith 2008; Bielfeldt et al. 2010), although there is evidence that silver has limited impact for lower levels of contamination (van Halem 2006) or no impact on microbial performance (Brown et al. 2007). Silver was shown to decrease the microbial growth within the filter (Bloem 2009; van Halem et al. 2010) which can contribute to contamination as shown by (Bielfeldt et al. 2010). Further research has sought to identify the variables associated with the use of silver in CWFs and the corresponding effects on performance (Kohler 2009; Lantange et al. 2010). The behavior of silver within the CWF microstructure has also been studied including the release over time (Lantange 2001a; Stewart 2010) and materials characteristics related to application method (Larimar 2010; Stewart 2010). CWF samples from the field have been collected and the potential exists to conduct materials analysis similar to other studies (Larimar 2010; Stewart 2010).

Appendix I Indicator Organisms

Total coliform bacteria are gram-negative rod bacteria that will, at 35 degrees Celsius, ferment lactose and create a distinctive colony. These mechanisms are the basis for the most probable number [MPN], presence/absence [P/A], and membrane filtration [MF] tests. Total coliforms include Klebsiella, Citrobacter, Enterobacter, and Escherichia genus with the later most commonly associated with waterborne disease. Total coliform bacteria are naturally found in the environment in the tropics and do not necessarily represent the presence of fecal contamination. For this reason other bacteria are often used as indicator organisms in addition to total coliforms.

Escherichia coli (E. coli) is a bacteria that is found in the gastrointestinal tract of mammals and necessary for proper metabolic function. Some strains of E. coli are virulent, however the majority are harmless, but since E. coli cannot survive for long periods outside of a host, its presence indicates fecal contamination. E. coli is however, less resistant to disinfectants than other pathogenic organisms (e.g. enteric viruses and protozoa) and therefore it is important to note that the absence of E. coli does not indicate freedom from all pathogens. Despite this E. coli is commonly used as a standard indicator organism for determining microbial contamination. For environments with lower contamination loading testing for total coliforms is used as there may be insufficient E. coli present to determine the efficiency of treatment processes (CDC, 2010).

As indicator organisms for cleanliness and integrity of distribution systems and treatment technologies total coliform and E. coli were chosen to be used when evaluating the efficiency of the ceramic water filters in this study (WHO, 2011). Quantification of bacterial contamination using membrane filtration is and economical and scientifically accepted method following the

Appendix I (Continued)

detection and enumeration methods (EPA Method 1604 or Standard Methods 9222). The recommended minimum sample numbers for fecal indicator testing in piped distribution systems serving populations less than 5,000 people is 12 samples per year. (Standard Methods 9308-1:2000).

Appendix J Ceramic Water Filter Hydraulic Performance

Table J-1 Publications reporting in-situ flow rates for ceramic water filters.

Reference.	Publication	Study Location	Sample Size	Flow Rate (liters/hour)			Ave. Fill Rate (#/day)	Ave. Family Size*
				Ave.	Min.	Max.		
Brown (2007)	UNICEF Field Note	Cambodia	80	NR	1	3	1.8	6
Brown and Sobsey (2008)	Am. J. Trop. Med. Hyg.	Cambodia	120	NR	1.5	3	NR	6
Lantagne (2001b)	NGO study	Nicaragua	24	0.98	0.13	3.5	1	5
Hwang (2002)	MS thesis-MIT	Nicaragua	76	1.71	1	2.9	2-3	5
Casanova (2011)	Conference proceedings	Sri Lanka	345	1.1	<1	>3	1-2	5

***Values rounded up.**
NR=Not Reported

Table J-2 Publications referencing flow rate or hydraulic performance

Reference	Location	# of Households	Comment on volume of water.
Al Moyed (2008)	Yemen	180	87% used water for drinking only
Brown (2007)	Cambodia	80	86% used water for drinking only
Brown and Sobsey (2008)	Cambodia	60	100% said filter met drinking water need
Hwang (2002)	Nicaragua	100	83% used water for drinking only
Johnson (2007)	Ghana	25	16% filter flow rate is too slow
Partners for Development (2002)	Cambodia	135	84% volume of water produced is sufficient
Walsh (2000)	Nicaragua	130	45% water is "sufficient"
Westphal (2008)	Nicaragua	43	86% used water for drinking only

Appendix K Sustained Use of Ceramic Water Filters

There are significant implications to giving away household water treatment devices, such as ceramic water filters. For example, in one willingness-to-pay study, when households were asked how much they could sell their filters for (as well as what the manufacturers should sell if for) they responded with $3.85-$5.38 which is considerably lower than the actual production cost of the filters $7.01 (Walsh, 2000). None of the 130 households in the survey paid for their filters, although a study of household income, previous purchases of comparably priced items, and expenditures on diarrheal disease revealed the ability to pay the actual filter cost in 93% of the households (Walsh, 2000). Access to credit did not seem to affect willingness-to-pay and the author concluded that subsidies would be necessary to increase marketability of filters. This demonstrates how distributing filters free of charge can negatively affect the marketability of filters and the willingness of households to invest in water and sanitation technologies.

Table K-1 shows a summary of the literature field studies of ceramic water filters including: price paid for filters, percent that paid for their filter, percent not using filter, and reasons for disuse. Few studies have collected rigorous information about willingness-to-pay, although there is anecdotal evidence suggesting that sustained use is linked to willingness-to-pay.

Appendix K (Continued)

Table K-1 Sustained use of ceramic water filters in field studies.

Reference	Bought filter (%)	Price paid (US$)	Retail Value (US$)		Not using (% households)	Definition of "Using"	Reason for Disuse (%)		
			Filter	Ceramic			Breakage Ceramic	Tap Issue	Filtration Rate
Roberts (2003 and 2004)	0%	---	$7.50	$4.50	35% (n=101)	Reported	20% (n=35)	71% (n=35)	NR
Brown et al. (2009)	42%	$0.25 – $2.50	$7.50-$9.50	$2.50-$5.00	69% (n=506)	Wet filter, Reported	65% (n=328)		5% (n=328)
Brown et al. (2008)	0%	---	$8	$2.50	2% (n=180)	Reported	0	0	100% (n=4)
Clopek (2009)	77%	$6-$20	$20	$6	54% (n=221)	Properly installed, water in filter and bucket	19% (n=118)	8% (n=118)	5% (n=118)
Walsh (2000)	0%	---	$7	$4	12% (n=130)	Reported	NR	NR	NR
Valerio, M (1999, 2000)	NR	NR	$7	$4	49% average (10-94%)	NR	NR	NR	NR
Lantagne (2001b)	20%	$4	$7-$64	$4	27% (n=33)	water in filter	66% (n=9)	n/a	33% (n=9)
Hwang (2002)	0%	---	$7-$64	$4	15% (n=100)	Reported	14% (n=100)	0% (n=100)	1% (n=100)
Westphal (2008)	NR	NR	NR	NR	49% (n=167)	NR	41% (n=81)	58% (n=81)	NR
Dundon (2009)	0%	---	$20	NR	NR	NR	NR	NR	NR
Al Moyed (2008)	0%	---	NR	NR	0%	Reported	0%	10%	13%
Narkiewicz (2010)	0%	---	NR	NR	40% (n=NR)	NR	NR	NR	NR

NR-Not reported

Appendix L Ceramic Water Filter Production Processes

Table L-1 below provides a description of the processes used to produce ceramic water filters, by the two manufacturers in the Dominican Republic. For more information on the production process variables see Raynor (2010).

Table L-1 Ceramic filter production processes

Process	**Instituto de Desarrollo de la Economía Asociativa (IDEAC)**	**FilterPure**
Clay Processing	Hammer mill followed by hand sieve	Hammer mill followed by hand sieve
Saw Dust Processing	Hammer mill followed by hand sieve	Hammer mill followed by hand sieve
Water Processing	None	Settling and decanting
Water Processing	None	Settling and decanting
Mix Ratio	Weight 12 lbs saw dust and 60 lbs clay, 2.5 gallons water (50% clay/50% saw dust)	60% clay 40% sawdust
Mixing	Mix dry by hand and add water and mix by hand on tarp for 10 mins	Mechanical mixing for 30 minutes in a diesel engine drum mixer.
Press	16 lb balls in a hydraulic press	16 lb balls in a hydraulic press
Total Dry time	3-5 days covered environment	5 days covered environment
Kiln	890 degrees celcius for 9 hours	600 degrees celcius for 4 hours
Silver	Painted on after firing	Mixed into water before firing
Silver Concentration	Unknown, however PFP recommends 2 mL of 3.2 percent colloidal silver in 250 mL of filtered water	Proprietary
Quality control	Flow rate testing (1.0-2.5 liters/hour)	Presence or absence of sulfate reducing bacteria. Testing is conducted on two filters out of every batch of 50.
Batch Size	Kiln capacity ~30 filters	Kiln capacity is 50 filters
Source:	http://www.youtube.com/watch?v=-2c2bmg7yCMandeurl=http://www.ideac.org.do/filtro/	FilterPure literature obtained from Lisa Ballentine

Appendix M Research Site Location

Figure M-1 Map showing the location of La Tinajita. Map shows the location of the laboratory in Santiago as well as the capital of the municipality (Pedro Garcia) and provincial capital (Puerto Plata).

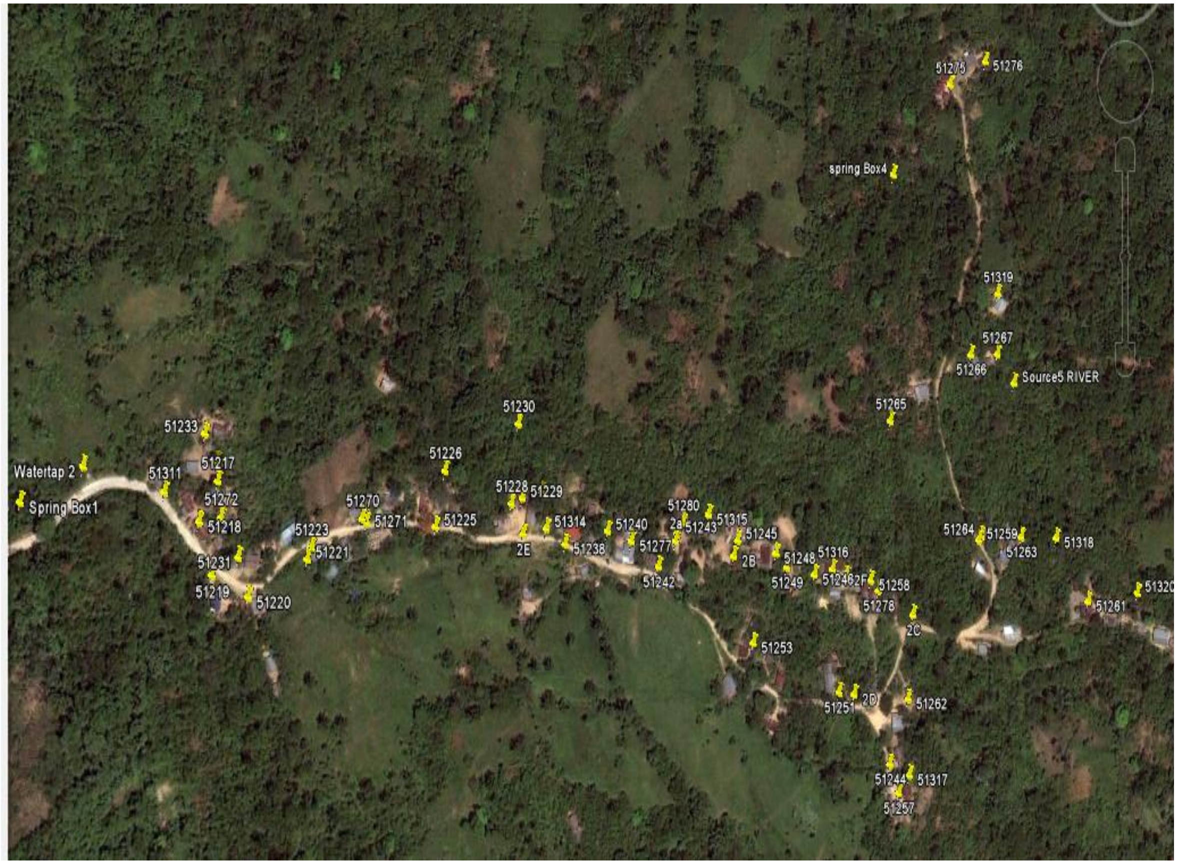
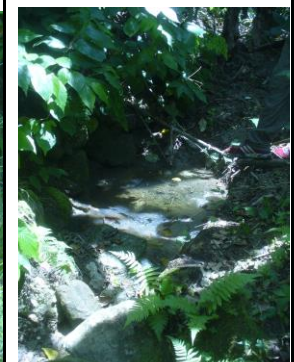


Figure M-2 Map of La Tinajita with location of 59 households.

Appendix N La Tinajita Water Sources

Table N-1 Description of the water sources in the community of La Tinajita

Source	Spring	Spring	Spring	Spring	River
Picture					N/A
Details	Engineers Without Borders University of Kentucky constructed a tank and rebuilt a crude spring box in 2009. Aqueduct built by the community in the 90s.	No springbox or intake structure. Spring is fenced in but in the middle of a cow pasture. Aqueduct constructed by community.	No springbox or intake structure. Aqueduct constructed by community.	No springbox or intake structure.	Agricultural lands and other communities upriver.
Households Served	18	19	14	2	3
Service Level	Household taps	Household taps	Household taps	Point Source	Point Source
System Storage Capacity	1,800 gallons	600 gallons	600 gallons	None	None
Contamination Risk	Intermediate to High	High	High	High	High

Appendix O Monthly Clinic Visits

Figures O-1 thru O-4 present the total number of clinic visits by patients of the community of La Tinajita. The data is disaggregated by disease/diagnosis, and was obtained from the medical records of the clinic. Clinic data represents monthly average visits and diagnoses over the past 5 years (2005-2010). The rainfall data was obtained from the meteorology station at Gregorio Luperón International Airport outside of the city of Puerto Plata (14 miles away from the community on the coast.) It represents monthly average data from 1970 to 2000.

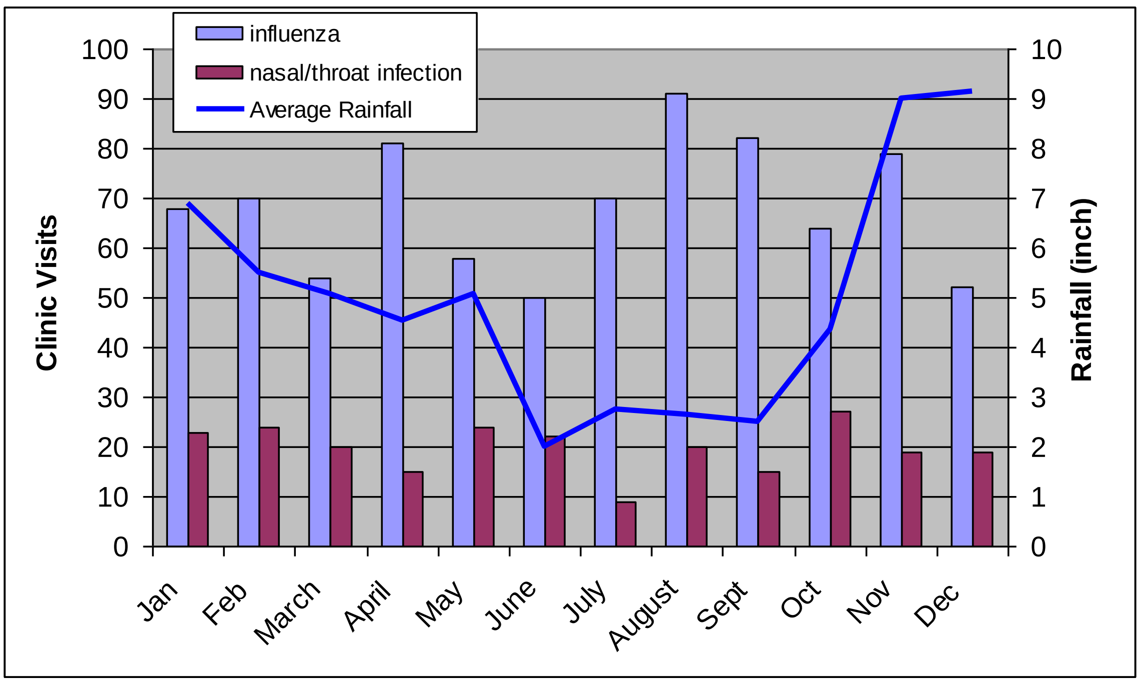


Figure O-1 La Tinajita monthly clinic visits due to influenza and nasal/throat infections.

Appendix O (Continued)

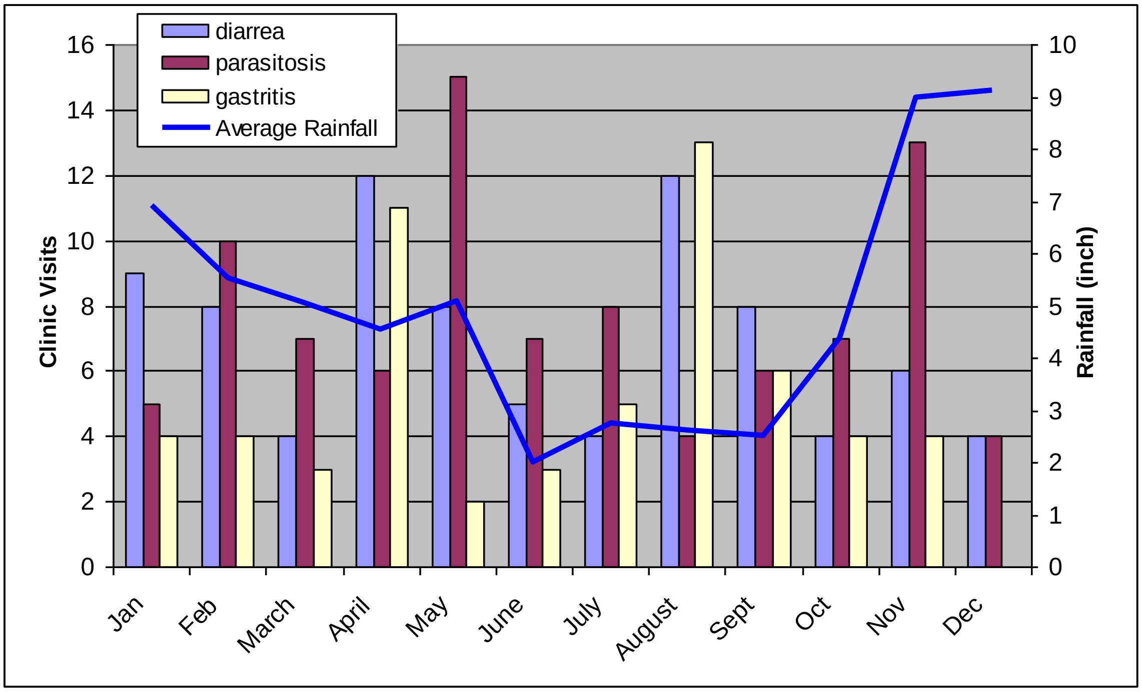


Figure O-2 La Tinajita monthly clinic visits due to diarrhea, parasitosis, and gastritis.

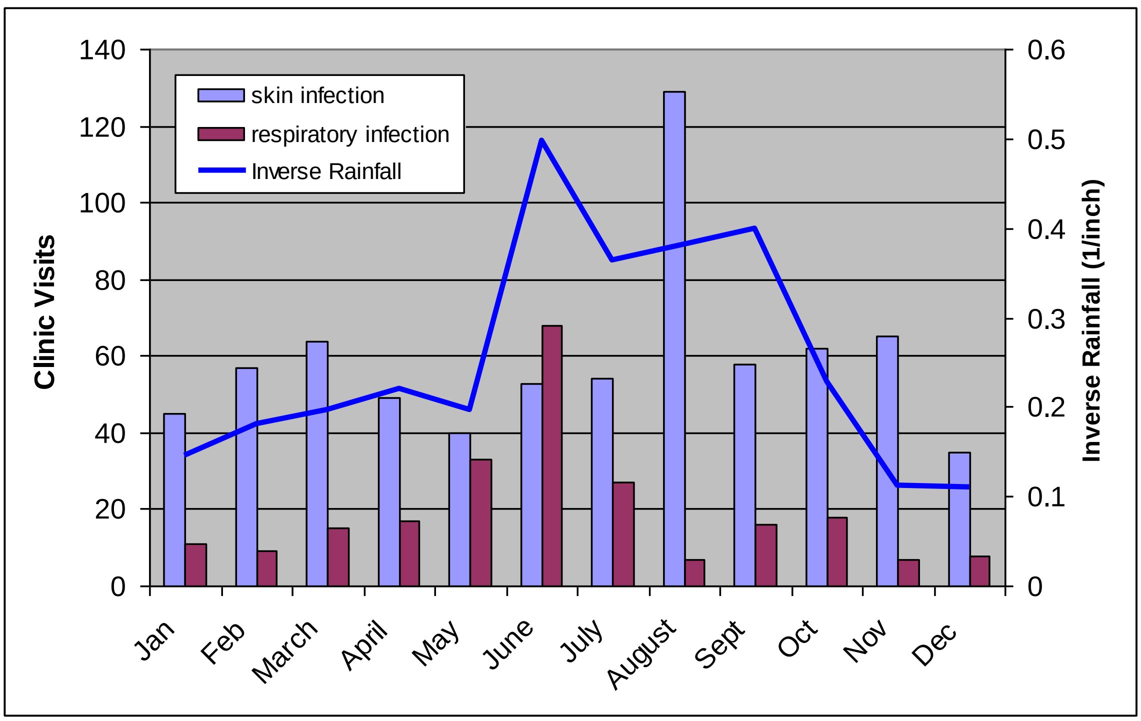


Figure O-3 La Tinajita monthly clinic visits due to skin and respiratory infection.

Appendix O (Continued)

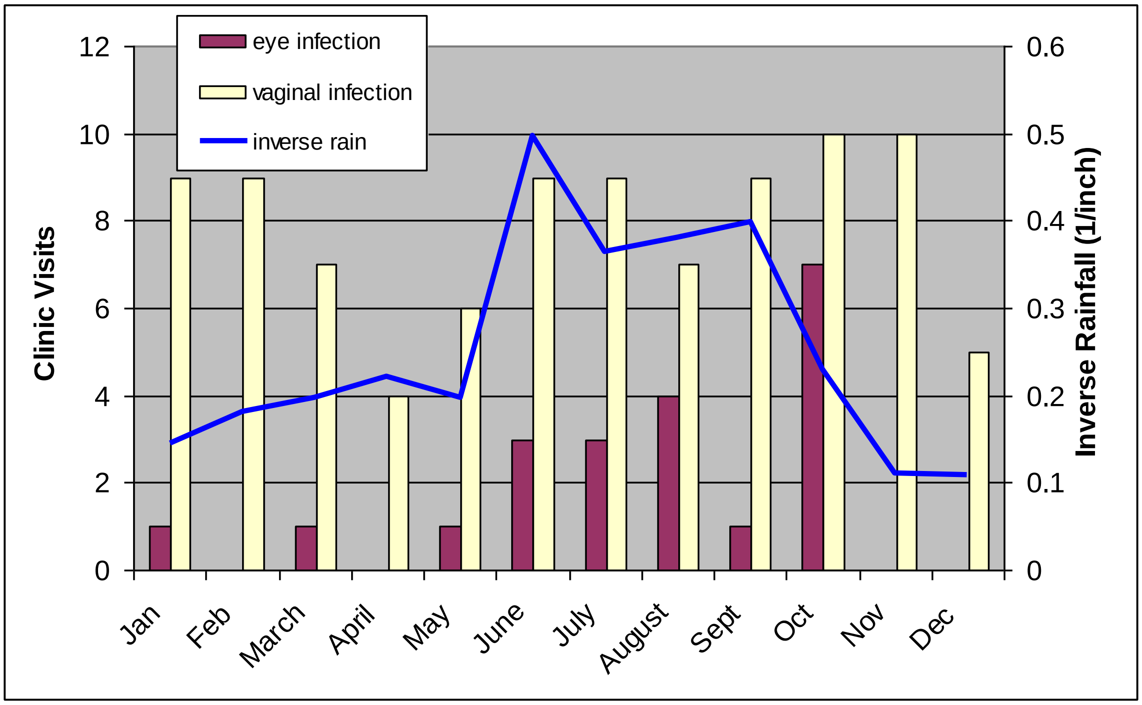


Figure O-4 La Tinajita monthly clinic visits due to eye and vaginal infections.

Appendix P Filter Distribution, Set-up, and Maintenance Procedures

The following section describes the procedures for the distribution, set-up, and maintenance of the ceramic water filters used in the field research described in Chapter 4. Filter distribution took place in the fall of 2010. On Sunday August 29th a member from each of the households in community received a ticket numbered 1 through 59 (the total number of households in the community). A training session was conducted on the set up (see "Filter Set up Procedure") and maintenance (see "Filter Maintenance Procedure") of the filters. After the training those with odd numbered tickets (30 households) were given Filter Pure filters and those with even numbered tickets (29 households) were given Potters for Peace filters (although the distribution of the PFP filters took place the following week Sunday September 5th). Each household was given a filter element, 5 gallon bucket with a spigot, a cover, and a brush (for exclusive use of scrubbing and cleaning filter).

The filter set-up procedure consisted of scrubbing the filters with a brush and clean water. During the training sessions, households were instructed to use boiled water to scrub the filters. This is done to remove dust and loose clay particles. Water was flushed through the filter until the filter had processed five filter volumes. Households were told to filter 3 five-gallon buckets (~ 5 filter volumes). The filters were scrubbed again with clean water and the buckets were washed out with clean water and soap.

Table P-1 Ceramic filter maintenance procedure for IDEAC and Filterpure filters

IDEAC	Filterpure
Scrub ceramic once a month or as needed. Maintain a "clean storage bucket by washing weekly with detergent and chlorine"	"Lightly scrub surface of filter when flow rate is reduced. Boil ceramic media every 3 months to ensure optimum effectiveness."

Appendix P (Continued)

The maintenance procedure for each of the different filters is shown in Table P-1. In order to be consistent the households were told to scrub the filter lightly each month, and boil the filter media every 3 months as recommended by Filterpure.

Appendix Q Institutional Review Board Clearance

USF
UNIVERSITY OF
SOUTH FLORIDA

DIVISION OF RESEARCH INTEGRITY AND COMPLIANCE
Institutional Review Boards, FWA No. 00001669
12901 Bruce B. Downs Blvd., MDC035 • Tampa, FL 33612-4799
(813) 974-5638 • FAX (813) 974-5618

May 12, 2011

James Mihelcic, PhD
Civil and Environmental Engineering
ENB118

RE: **Expedited Approval** for Continuing Review
IRB#: Pro00001074
Title: Dominican Republic Ceramic Filter Study

Study Approval Period: 6/10/2011 to 6/10/2012

Dear Dr. Mihelcic,

On 5/11/2011 the Institutional Review Board (IRB) reviewed and **APPROVED** the above protocol **for the period indicated above**. It was the determination of the IRB that your study qualified for expedited review based on the federal expedited category number:

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

Also approved was the waiver of documentation of informed consent.

Please reference the above IRB protocol number in all correspondence regarding this protocol with the IRB or the Division of Research Integrity and Compliance. It is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

John Schinka, PhD, Chairperson
USF Institutional Review Board

Figure Q-1 Institutional Review Board clearance letter.

Appendix Q (Continued)

USF
UNIVERSITY OF
SOUTH FLORIDA

DIVISION OF RESEARCH INTEGRITY AND COMPLIANCE
Institutional Review Boards, FWA No. 00001669
12901 Bruce B. Downs Blvd., MDC035 • Tampa, FL 33612-4799
(813) 974-5638 • FAX (813) 974-5618

September 18, 2012

James Mihelcic, Ph.D.
Civil and Environmental Engineering
4202 E Fowler Ave, ENB118
Tampa, FL 33620

RE: **Acceptance of** Application for Final Review
IRB#: Pro00001074
Title: Dominican Republic Ceramic Filter Study

Dear Dr. Mihelcic:

On 09/17/2012, the Institutional Review Board (IRB) reviewed and **ACCEPTED** your Application for Final Review/Closure.

Please be advised that you are required to maintain complete research records including all IRB documentation, source documents, and (if applicable) informed consent/assent documents for all subjects who participated in this study for a minimum of five years after completion of the research (end of IRB-approval) or for the period designated by the study sponsor and/or oversight agency or HIPAA, whichever period is longer.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

John Schinka Ph.D., Chairperson
USF Institutional Review Board

Figure Q-2 Institutional Review Board final review letter.

Appendix R Select Baseline Survey Results

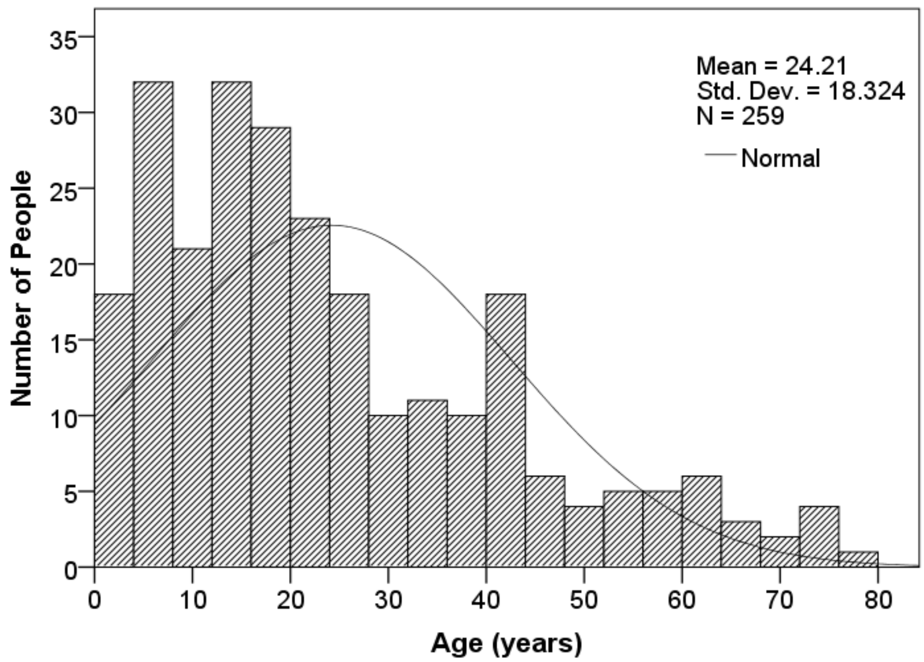


Figure R-1 Population frequency histogram for La Tinajita.

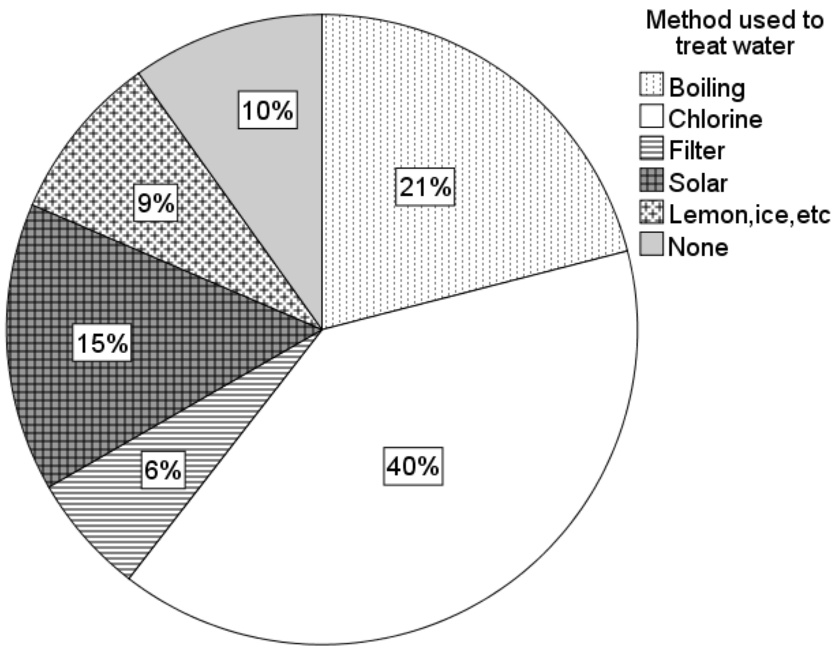


Figure R-2 Household water treatment methods prior to receiving filters.

Appendix S User Acceptability

Fifty-nine households initially agreed to participate in the research and received a filter, a brush for cleaning, and training in the proper operation and maintenance. When the milestone survey was conducted in June 2011, only forty-four households were using the filter. The reasons given for disuse of the filter are shown in Table S-1.

Table S-1 Reasons cited for disuse of filter in longitudinal field study in La Tinajita.

Number Households	Reasons Cited
5	Do not believe or trust that filter works
4	Do not believe water needs to be filtered
4	Inconvenient
2	Moved out of the community

Based upon the household surveys, there were four main issues that were expressed by users. These are: filtration rates are unacceptably low, tap or sealing gasket leaks, lid does not appropriately cover the filter, and ceramic is misshapen leaving a gap. Figure S-1 shows an example of a filter is a misshapen lid. Users expressed concern that insects such as cockroaches could enter the filter at night if it wasn't properly covered.

Figure S-1 Photo of a distorted lid that does not adequately cover the filter.

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Figure S-2 Photo of manufacturing defect in filter.

Figure S-2 shows a manufacturing defect in a ceramic membrane which has left it misshapen. A significant gap between the ceramic and the plastic storage vessel is a potential entry way for contaminants.

In response to the identified issues, households that complained of low filtration rates were visited. The flow rate was measured and households were instructed to clean and vigorously scrub their filters following manufacturer's guidelines (see Appendix R). If upon a repeated visit the filtration rate was below 250 mL an hour the filter was replaced. In the first year of the study 6 filters were replaced due to slow filtration. All dysfunctional gaskets and taps and misshapen ceramic units were replaced as well as 8 filters that were broken or damaged. The decision was made not to switch out malformed lids as most households had developed a system for covering their filters (See photos in Figure S-3).

Appendix S (Continued)

Figure S-3 Household strategies to improve filter hygiene in La Tinajita.

Appendix T Regulatory Laws

In the Dominican Republic the regulatory framework governing potable water is divided into two domains: retail water and non-retail water. Bottled water and other packaged water sold in discrete units to the public (as opposed to meter water delivered via distribution networks) are governed by the Dominican equivalent of the Food and Drug Administration. All other potable water is regulated through the General Health Law (Ley 42-01) and enforced by the Secretariat of Public Health. Seventy-five parameters are controlled under this law including: undesired substances (23), toxic substances (15), chemical (14), complementary (6), physical-chemical (5), radioactive (2), and disinfectants (1)

The minimum monitoring protocol requires monthly analysis for the following parameters: odor, taste, turbidity, conductivity, nitrates, ammonia, total coliforms, fecal coliforms, and residual chlorine. Law 42-01 also specifies the minimum necessary quantity to water to maintain basic function: 2-2.5 liters/person/day or the equivalent to 3% of the average weight of the person. Internationally The World Health Organization also has recommended water quality standards. These are shown in the Table T-1 along with the corresponding values for DR Law 42-01, and the ranges observed during the first year of field study.

Table T-1 Domestic and international water quality regulations

Characteristic	Dominican Republic Law 42-01	World Health Organization	Range Observed in Field
Turbidity	<5 (10)[*] NTU	<5	0-10
Color	<10 (50) Hazen Units	<15 Hazen Units	Not measured
pH	7.0-8.5 (6.5-9.2)	NE	6.5-8.1
Total Coliforms	0 (10[†])	0	0 to >2,000
Fecal Coliforms	0	0	0 to> 2,000

[*]-Number in parenthesis is the maximum allowable
[†]-For distribution networks 5% of the samples may have values over 0 CFU/100mL but no individual value may be above 10 CFU/100mL.

Appendix U Summary of Focus Group Meetings

The following sections are summaries of two focus group discussions that took place in the community of La Tinajita in June of 2010. Two groups of eight women each were asked 15 questions and participated in two activities. The notes from these two meetings are summarized below.

The first focus group took place with eight women who had received FilterPure filters. The following section describes this focus group meeting. The first question was: Who had seen a ceramic filter before this project and where did you see it? Response: No-one had seen a ceramic water filter before but 3 women mentioned filters that are used in "the city" (Santiago de los Caballeros) that "are long and round and attached to the kitchen faucet." These are likely granualar activated carbon filters. One woman also said that "there are filters that use sand, in [a neighboring community]." Three other woman confirmed having seen these filters, but did not comment on their perceptions regarding filter performance. Finally, a woman added that there is such a filter [sand filter] in the community that was installed by Rita, the founder of the local rural clinic. Supposedly, the household discontinued use because it filtered slowly.

The second question was: Think of the time when you first saw your filters—What did you think? Response: One woman explained that she thought that the ceramic media looked like a planter and was "curious" as to how it could be used to filter water. One woman said she did not know if it would function (i.e.-if the water flow) upwards or downwards. One woman admitted that the first time that she used her filters she "was left observing it to understand how it worked and how the ceramic sweat the water."

Appendix U (Continued)

The third question was: Now, tell me how your opinions about your filter have changed? Response: One woman said she had stomach problems, and before she did not know what was causing them, but after drinking water from the filter, she does not have stomach problems.

The fourth question was: Do you use your filter? Response: All eight women reported using their filters, although at least two of the eight women had dry filters during the household visits conducted in the two days prior to the meeting.

The fifth question was: What do you use the filtered water for? Response: All eight women said they use their filtered water for drinking. Only one woman said that she used the filtered water for another purpose (bathing her infant). And this was "infrequent as there is not enough water [for bathing her infant]."

The sixth question was: What are the water sources in the community? Response: The women listed rain, river, spring, and bottled water. Next the women were asked to participate in two activities. During the first activity the women were then asked to place these in order of most preferable to least preferable using pictures of each. Each woman was asked to explain her choice. All eight women ranked spring water the highest and river water the lowest, but disagreed on the order of rainwater and bottled water. In their justifications for why a certain water source was preferred they often cited which water they relied upon more often. Six women admitted using spring water the most and rain water when available. The other two women ranked bottled water as preferred over rainwater. One woman said "I use spring and bottled water most because rain and river water are contaminated." Other women said they liked rainwater because it is the best water for softening dried beans and that when it was used to boil plantains it did not discolor them. One woman complained that groundwater did not "sud up as much" and that one uses too much soap to wash with. This is likely due to higher hardness of groundwater.

During the second activity the women were then asked to arrange the pictures from best water quality to worst water quality. The women were split, half thought bottled water was the best quality and the other half thought rainwater was the best quality. Two women expressed concerns surrounding the quality of rainwater as it is dependent on the potential sources of contamination from the roof. One woman said that she does not trust rainwater because it has a bad taste and "you do not know what [contamination] is in on the roof. Another said it causes your belly to grow-presumably with parasites. The women all expressed concern of the high cost of bottled water, which is not sold in the community. A 5 gallon bottle costs 40 RD (37 RD = 1 US$) and a motorcycle taxi to the nearest vendor costs 60RD roundtrip.

One woman stated "I will drink what you serve me in your [the author's] house but I have never bought water and never will." The same woman reported washing her cloths and bathing in the river but stated that it is no longer safe to drink. Another woman added that you cannot drink from the river "because you do not know what will come down it." River water was cited as a source of vaginal infections or "women's infections." When it rains the women said the increase in turbidity leads them to believe that the water is unsafe to drink-this increase also occurs in the water within the water system. During these times the women reported collecting rainwater.

All women recognized the danger in using river and spring water during or after rains as the turbidity increases. During these periods the women who use these sources switch to rainwater. One woman said she uses tapwater only when the rainwater runs out.

Appendix U (Continued)

Six out of eight women had children 5 years of age or younger, three of whom prepared formula or powdered milk with water for their children. One woman used bottled water or filter water if there was not money to buy botellons. The other two women would boil filter water or rain water. After the activities, the meeting format returned to open question and response.

The seventh question was: In the future would you buy a filter if yours broke- If so how much would you pay? Response: Only one woman said she would definitely be willing to buy a filter if her's broke. One of the women said "Moca (where the FilterPure factory is located) is far away…you are going to spend [money] to arrive there and afterwards on the filter and return trip?" Women said they would pay 130, 150, 200, 300, 300, 500, 1000 RD for a filter. The retail price of the filters is approximately 800 RD and roundtrip transportation costs are approximately 400 RD.

The eighth question was: What are the things that you like about your filter? Response: One woman stated that she liked how it filters "the water passes but you do not even see any holes…" Five cited the taste as an important factor. One stated that it "does not taste like what we used to drink." Other women were curious how a filter could be made out of earth. Compared to treatment with chlorine the filter is more convenient "because you do not have to wait." Another said "You can see the contaminants being removed" which accumulate on the inside of the filter, however in no household was any sediment observed inside the filters. One woman gave a testimonial that her stomach used to hurt all the time but after drinking filtered water it no longer does.

The ninth and final question was: What are the things that you do not like about your filter?

Appendix U (Continued)

Response: One woman stated that she wished the tap on the bucket had a cover to protect it from insects- "cockroaches can get in there." Two other women supported this complaint. Another woman said that the covers were not ideal, and that they should cover everything. One woman suggest that the design could be modified so that the filter media was nested down inside the bucket so the lip did not come outside the bucket and then a "normal" cover to the bucket could be used.

Following this focus group a second focus group was held using the same format (open ended questions, discussion style format with two activities). The second group of participants were the women head of households who had Potters for Peace (IDEAC) filters. The first question was: Have you seen a ceramic filter before you received this one? Response: No participants had seen a ceramic water filter prior to the study.

The second question was: Think about when you first received the filter. What were your initial thoughts? Response: Before receiving the filter: Some participants had seen the Rotary Club biosand filter and expected this filter to be similar. One of the women thought that she would have to install the filter in her house and worried that she would not be able to because her house is made of wood. Upon first seeing the filter one woman admitted thinking: "How is the water going to pass through that?" Most of the participants, having never seen a ceramic filter before, did not understand how the filter would filter anything. They thought it would just hold the water and not filter it. Upon first use one woman admitted asking herself: "What am I supposed to do with that little bit of water?" Some participants were concerned with the flow rate and thought it was too slow. Others thought that the flow rate was acceptable.

The third question was: If the flavor does not change then what is it filtering? Response: All participants except for one said that the filter did not change the flavor of the water. Several of them said that they did not think that the filter was cleaning the water because the flavor of the water was not changing. One participant explained this by saying that people expect clean water to taste like purified bottled water, which tastes different than rain or spring water. So when rainwater or spring water was put in the filter and came out tasting the same and not like purified bottled water they did not think that the filter had done anything.

The fourth question was: How has your opinion of the filter changed? Response: The participant who reported the flow rate being too slow at first said that it has since increased and is now acceptable. "At first it filtered fine but now it does not filter anything." Four participants reported that their filters no longer filtered enough water for their household. As a result they were drinking unfiltered rainwater or tap water in addition to whatever their filter produced. "El sabor no cambia." Several of the participants still had doubts about what the filter was doing if it did not change the flavor of the water. Only one participant said that she thought the water was being filtered even if the taste was not changing. Others seemed to think that the filter was worth using but the doubts about whether it was really working remained the same. They continue using it because it filtered out the visible things but it is questionable whether many of them fully trust the filter.

The fifth question was: Do you use the filter? Response: One of the women stopped using her filter because the flow rate was too slow. The other three who reported slow filtration rates said that they still fill it but have to drink unfiltered water as well.

The sixth question was: What are the sources of water in the community? Response: Rainwater, tap water, and purified bottled water were the three answers given. River water was not mentioned and when asked about it the participants said that nobody uses it for drinking.

Similar to the previous focus group activity the women were asked to place the different types of water in order from the most preferred to least preferred and then later from best quality to worst quality. Response: The participants were not able to articulate which water was of the best quality, nor could/would they suggest criteria for how one might judge water quality. One participant was aware of the benefit of spring water being filtered in the ground but preferred rainwater anyway. Most participants were in agreement over water preference. Two said that they always put tap water in the filter regardless of rainfall. Both of them receive water from the same water source (Source 3) whereas the other participants had different tap water sources. The other six said that they always put rainwater in the filter if they can and do not like the taste of tap water. In all cases taste was the most important factor in deciding which water to drink.

The seventh question was: Why do you use filtered water instead of buying purified bottled water? Response: Two participants said that they do sometimes buy bottled water. Large 5 gallon bottles of water are not sold in the community. It is expensive to purchase one and have it delivered.

The eighth question was: Would you buy a filter if yours broke or you did not have one? Response: "If there was money to pay for one I would, but usually there are more things to buy than there is money and you might have to spend the money on something more important." Most of the participants said that they would not buy another filter if theirs broke because they do not have enough money. One woman said, "I take very good care of my filter because I like it but if it broke I would not be able to buy a new one." Nobody said that they would definitely buy a new one if their current one broke.

The ninth question was: What do you like about the filter? Response: "All of the parasites and little insects stay in the filter." "It holds a lot of water." "The water stays colder in the filter than in the rainwater tank." One participant compared it to the clay water storage tanks used in the country that keep water cooler. "The water tastes better because it is cold." "The top protects the filter and does not let anything fall in the water." "You do not have to dump out rainwater after a few days because you can just put it in the filter. Without the filter it would be too dirty after a couple of days." In addition the women were asked what they did not like about the filters. Responses included: "It does not filter very much." "It does not change the flavor of the water." "The top does not fit right."

The women were also asked to provide any additional comments or feedback. One participant said that she sometimes uses solar disinfection (also called SODIS) and that it changes the flavor of the water for the better. Several participants said that the filter has a faster flow rate after cleaning it. "In a house with many people it does not provide enough water so even though we want to always drink filtered water we are not able to." One participant suggested that a cap be included for the spigot to keep it clean inside.

Appendix V Geometry Measurement Procedures[25]

In order to measure the depth of water in each filter, a special device was made that has a ruler attached to an adjustable slider. This slider creates a 90 degree angle with a cross piece forming a "T" shown in Figure V-1. This cross piece rests on the lip of the filter and the slider is adjusted so the ruler rests on the bottom, inside the filter. The ruler is used to measure the height of the water inside the filter. These measurements are used for initial water depth (h_0) and subsequent water depths ($h(t)$) for the falling head tests, and when determining the shape parameters a and n for the paraboloid filter.

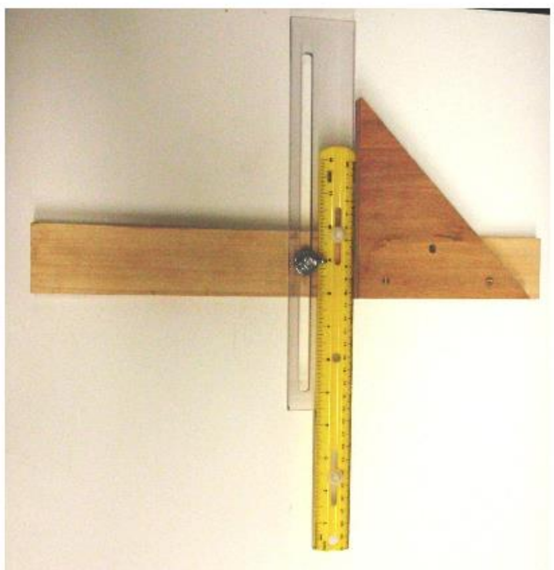


Figure V-1 Adjustable "T-device" used to measure falling head

[25] The remainder of this appendix is based upon the Supporting Information section of the article: Schweitzer, R.W., Cunningham, J.A., & Mihelcic, J.R. (2013) "Hydraulic Modeling of Clay Ceramic Water Filters for Point-of-Use Water Treatment." *Environ. Sci. Technol.* 47(1):429-35. doi: 10.1021/es302956f. Copyright 2013 American Chemical Society. This Supporting Information is available free of charge at http://pubs.acs.org/doi/suppl/10.1021/es302956f

Appendix V (Continued)

Filter sidewall thickness was measured using an outside transfer firm-joint caliper, which allows a measurement to be taken after the jaws of the caliper have been moved. Sidewall thickness measurements were taken at distance of at least 5.0 cm below the inside-top of the ceramic. The thickness of the bottom was measured by subtracting the maximum inside depth of the filter (found using the T device) from the total height of the filter measured with a steel tape measure (see Figure V-2). This was performed for both filter geometries.

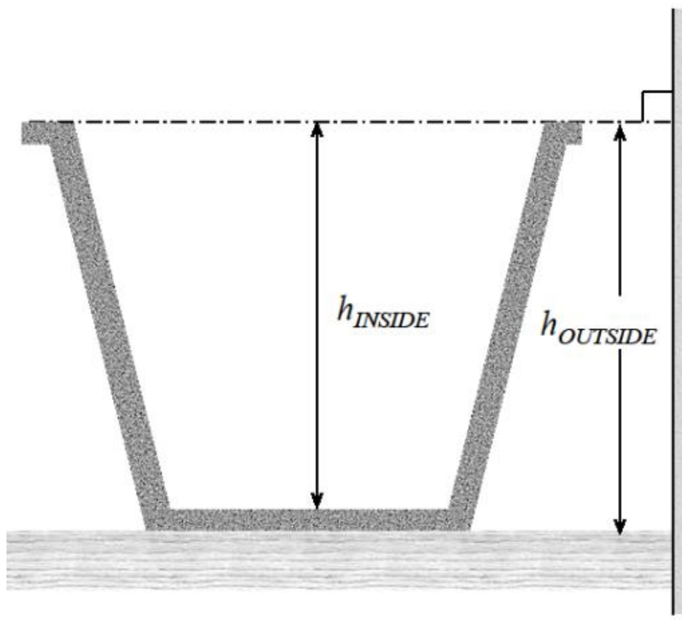


Figure V-2 Schematic diagram indicating how thickness of filter bottom is measured. The inside height (h_{INSIDE}) was determined used the T-device and the outside height ($h_{OUTSIDE}$) was determined using a steel tape measure and carpenter's square. The outside height for the paraboloid filter was determined by first flipping the filter upside-down so it could rest.

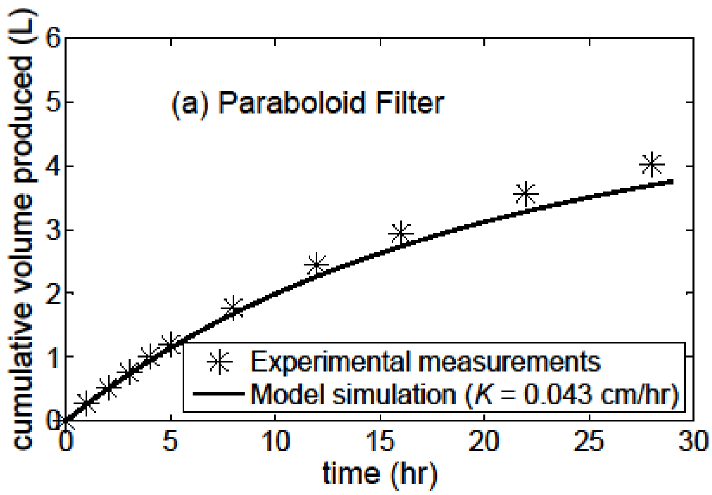
Appendix W Cumulative Volume of Filtrate and Volumetric Flow Rate

Figure W-1 presents the experimental data of cumulative volume produced in the falling head tests, $V(t)$, along with the predicted values from the calibrated model for both the paraboloid filter (Figure W-1a) and frustum filter (Figure W-1b). Figure W-2 presents the experimental data of volumetric flow rate during the falling-head tests, $Q(t)$, along with the predicted values from the calibrated model. Experimental estimates of $Q(t)$ were made by measuring the volume of filtrate, V, at time $t-\Delta t/2$ and at time $t+\Delta t/2$, and then calculating $Q(t) = [V(t+\Delta t/2)-V(t-\Delta t/2)]/\ \Delta t$. Thus, a measurement of $Q(t)$ represents the average flow rate over a time interval t but centered at time t. In both Figure W-1 and Figure W-2, the model predictions use the estimates of hydraulic conductivity, K, described in Chapter 5. These estimates of K were obtained from the calibration with water level data, $h(t)$.

For the frustum filter, the model predictions for $V(t)$ are very close to the experimental data. The estimate of hydraulic conductivity (K = 0.028 cm/hr.) fits both the $h(t)$ data and the $V(t)$ data very closely. For the paraboloid filter, the model estimate of $V(t)$ slightly under-predicts the experimental data when using K = 0.043 cm/hr. as obtained from the $h(t)$ data. Calibrating the model with the $V(t)$ data rather than the $h(t)$ would yield a slightly higher estimate of K, approximately 0.047 cm/hr. (1.3×10^{-7} m/s).

With regard to the volumetric flow rate $Q(t)$, the model predictions are in reasonable agreement with the experimental data for both the frustum filter and the paraboloid filter. There is some "scatter" or "noise" in the experimental measurements of $Q(t)$, but it is nonetheless clear that the model predictions are in good agreement with the experimental measurements.

Appendix W (Continued)



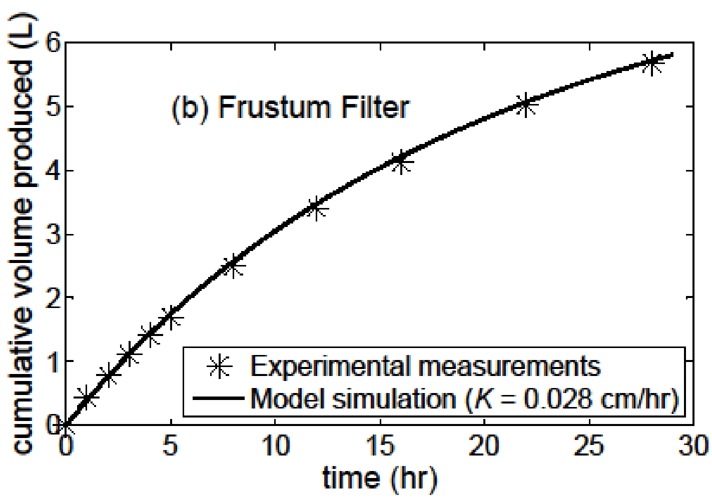


Figure W-1 Experimental measurements and model simulations for cumulative volume. Experimental measurements are from the falling-head laboratory tests with the calibrated model simulations for cumulative volume as a function of time since filling. Values of *K* were 0.043 cm/hr. (1.2×10^{-7} m/s) for the paraboloid and 0.028 cm/hr. (0.78×10^{-7} m/s) for the frustum shape

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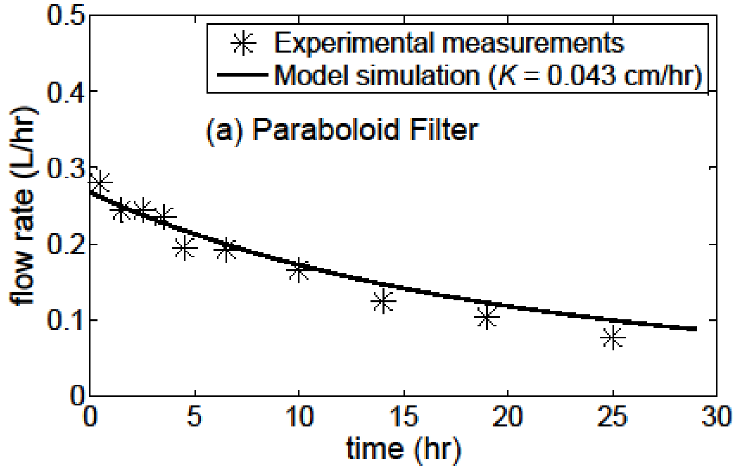
Appendix W (Continued)



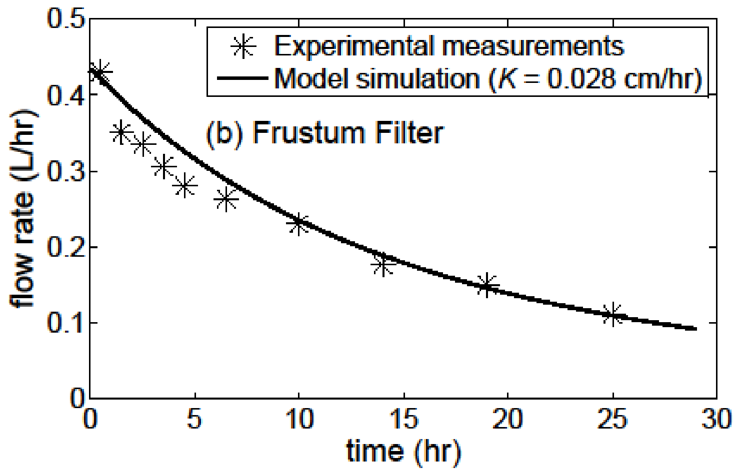


Figure W-2 Experimental measurements and model simulations for volumetric flow rate. Experimental measurements are from the falling-head laboratory tests with the calibrated model simulations for instantaneous volumetric flow rate as a function of time since filling. Values of *K* were 0.043 cm/hr. (1.2×10^{-7} m/s) for the paraboloid and 0.028 cm/hr. (0.78×10^{-7} m/s) for the frustum shape