EFFECTIVENESS OF CERAMIC FILTRATION FOR DRINKING WATER TREATMENT IN CAMBODIA

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ABSTRACT

JOSEPH MARK BROWN: EFFECTIVENESS OF CERAMIC FILTRATION FOR DRINKING WATER TREATMENT IN CAMBODIA
(Under the direction of Mark D. Sobsey, Ph.D.)

For the estimated 66% of Cambodians without access to improved drinking water sources and the potentially much greater percentage without consistent access to microbiologically safe water, point-of-use water treatment coupled with appropriate storage to prevent recontamination is a promising option for securing access to safe drinking water. The ceramic water purifier (CWP) is an emerging point-of-use water treatment technology that is made locally in Cambodia and in several other developing countries based on a design originally developed in Latin America in the 1980s. Despite the filter's increasingly widespread promotion and implementation as a public health intervention within Cambodia and worldwide, its effectiveness in reducing waterborne microbes and diarrheal disease in users has not been adequately characterized. This dissertation examines: (i) the microbiological effectiveness of locally produced ceramic filters in Cambodia against bacterial and viral surrogates in the laboratory and in field use; (ii) the health impacts of the CWP and a modified CWP in a randomized, controlled trial in a rural/peri-urban village; and (iii) the continued use, microbiological effectiveness, and sustained health impacts of the CWP after up to 44 months in household use in three provinces of Cambodia.

Results indicate filters as currently produced do reduce microbial indicators in drinking water and contribute to the reduction of diarrheal disease in users. Key findings were: (i) CWPs reduced *E. coli* up to 99.9999%, with mean reductions of approximately 99% in both laboratory and field testing; (ii) CWPs reduced MS2, a viral surrogate, by a mean 90-99% in laboratory testing; (iii) use of the CWP reduced diarrheal disease outcomes by approximately 40% in users versus non-users, after controlling for clustering within households and within individuals over time in a randomized, controlled trial; (iv) filters maintained effectiveness over long periods, up to 44 months in field use; (v) declining use of the CWPs after implementation was observed due to breakages of the ceramic filter elements coupled with limited availability of replacement parts in communities; and (vi) CWPs in field use were susceptible to recontamination through improper handling practices.

I am forever indebted to my longsuffering bride, my wise and patient mentors, my generous benefactors and enablers, my steadfast friends and family, and my loyal dogs.

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LIST OF ABBREVIATIONS

AIDS	Acquired Immune Deficiency Syndrome
BMJ	British Medical Journal
BSF	BioSand Filter
CDC	Centers for Disease Control (US)
cfu	Colony Forming Units
CI	Confidence Interval
CWP	Ceramic Water Purifier
CWP1	Ceramic Water Purifier as made by Resource Development International
CWP2	Ceramic Water Purifier (CWP1 modified by adding FeOOH)
CWP3	Ceramic Water Purifier (CWP1 without $AgNO_3$ or other amendments)
DAL	Double Agar Layer
DI	Deionized
EPA	Environmental Protection Agency (EPA)
g	grams
GEE	Generalized Estimating Equations
HAV	Hepatitis A Virus
HEV	Hepatitis E Virus
HIP	Hygiene Improvement Project
HIV	Human Immunodeficiency Virus
hr	hour
HWT	Household Water Treatment
HWTS	Household Water Treatment and Safe Storage

ICAITI	Instituto Centroamericano de Investigación y Technología Industrial
IDE	International Development Enterprises
IDWSD	International Drinking Water and Sanitation Decade
INPHWTSS	International Network to Promote Household Water Treatment and Safe Storage
IOSSF	Intermittently Operated Slow Sand Filter, e.g., the BioSand Filter
IRB	Institutional Review Board, University of North Carolina – Chapel Hill
IRC	International Water and Sanitation Centre, (Delft, Netherlands)
IRR	Incidence Rate Ratio
l	liters
LRV	Log_{10} Reduction Value
m	Meters
MDG	Millennium Development Goals
MF	Membrane Filtration
mg	milligrams
mo.	Month(s)
NAP	National Academies Press (United States)
NGO	Non-governmental Organization
NIS	National Institute of Statistics (Cambodia)
NRC	National Research Council
NSF	National Sanitation Foundation (now NSF-International)
NTU	Nephelometric Turbidity Units
ORT	Oral Rehydration Therapy
PBS	Phosphate-Buffered Saline

PDWS	Primary Drinking Water Source
PfP	Potters for Peace
pfu	Plaque Forming Units
pH	Pouvoir hydrogène
POST	Parliamentary Office of Science and Technology (United Kingdom)
POU	Point-of-Use
PPR	Prevalence Proportion Ratio
rcf	Relative Centrifugal Force (multiples of the force of gravity at sea level)
RDI	Resource Development International
RNA	Ribonucleic Acid
RO	Reverse Osmosis
RR	Rate Ratio
SAL	Single Agar Layer
SES	Socio-Economic Status
SODIS	Solar Disinfection system
TSA	Tryptic Soy Agar
TSB	Tryptic Soy Broth
UNC-CH	University of North Carolina – Chapel Hill
UNCED	United Nations Conference on Environment and Development
UN	United Nations
UNICEF	United Nations Children's Fund
USEPA	United States Environmental Protection Agency
UV	Ultra-Violet

WHO	World Health Organization
WQHC	Water Quality and Health Council (trade association, United States)
WSH	Water, Sanitation, and Hygiene

CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 Introduction

Over 1.1 billion people worldwide lack access to improved drinking water sources, and many more lack access to safe water as defined by the WHO risk-based Guidelines for Drinking Water Quality (10^{-6} Disability Adjusted Life Years per person per year) (WHO 2006; WHO 2004). Conventional piped water systems using effective treatment to deliver safe water to households may be decades away in much of the developing world, meaning that many of the poorest people must collect water outside the home and are responsible for managing (e.g., treating and storing) it themselves at the household level (Sobsey 2002). This gap in service is a serious public health issue and has been addressed in the Millennium Development Goals, which aim to halve, by 2015, the proportion of people without access to safe water in 2000 (UN 2000). Unsafe drinking water contributes to a staggering burden of waterborne disease in developing countries, borne primarily by the poor. Particularly susceptible are children, the elderly, and immuno-compromised individuals, who are most vulnerable to diarrheal and other waterborne infectious diseases.

In response to the persistent problems associated with waterborne diseases worldwide, new strategies for safe water provision are gaining currency, including treating drinking water at the household level to reduce the ingestion of pathogenic microbes. Taken together, devices that can be used to treat water and/or prevent contamination of stored water in the home are referred to as household water treatment (HWT) or point-of-use (POU) technologies. These comprise a range of options that can enable individuals and communities to reduce microbial pathogens or chemical contaminants in collected water at the point of use, usually at the household level. POU technology has the potential to fill the service gap where piped water systems are not possible, potentially resulting in substantial positive health impacts in developing countries (Sobsey 2006). Recent meta-analyses of field trials have suggested that household-based water quality interventions such as appropriate treatment and safe storage are effective in reducing diarrheal disease (Fewtrell *et al.* 2005; Clasen *et al.* 2006a, 2007).

Many technologies for POU water treatment exist and some are supported by extensive laboratory and field studies documenting effective reduction of waterborne pathogens and diarrheal disease in users. One promising technology is porous ceramic filtration. Recent studies of commercially produced ceramic filtration devices have suggested that they do provide an effective barrier against microbial pathogens in water and that interventions are associated with significant health gains in users versus non-users of the technologies (Clasen *et al.* 2004a; Clasen 2004b; Clasen *et al.* 2005; Clasen *et al.* 2006b). Locally produced ceramic filters, however, have not been rigorously evaluated in systematic field studies to determine microbiological effectiveness, impact on diarrheal disease, or continued effectiveness over time in field use, despite increasingly widespread production and distribution of these interventions throughout the developing world. As is the case with all candidate POU water treatment technologies, critical evaluation of the filter's sustained impact on water quality and human health is needed to inform current and potential users, implementers, and decision makers.

This dissertation includes three studies that add to the current knowledge of the potential role of locally produced ceramic water filters in providing access to safe drinking water in developing countries. These studies assess: (i), the microbiological effectiveness of locally produced ceramic filters (the CWP, or *ceramic water purifier,* together with two modified versions of the CWP) in Cambodia against bacterial and viral surrogates in the laboratory and *E. coli* in field use; (ii), the health impacts of the CWP and a modified CWP in a randomized, controlled trial in a rural/peri-urban village; and (iii), the continued use and sustained impact of the CWP after up to 44 months in household use in three provinces of Cambodia. These studies and their rationales are articulated below as research objectives.

1.2 Objectives

1.2.1 Objective 1

The first objective of this research was to evaluate the microbiological effectiveness of locally manufactured ceramic water filters against bacterial and viral pathogen surrogate microbes under laboratory and field use conditions. Detailed information on microbial reductions is not available for the most widely used locally-produced ceramic water filter in developing countries, including models produced in Cambodia (the CWP).

1.2.1.1 Hypothesis: objective 1

Study hypotheses were: (i) that locally-produced ceramic filtration technologies in Cambodia, including filters with and without iron oxide and $AgNO_3$ amendments, have the potential to achieve a mean 90-99% reduction in viral surrogates and a mean 99% reduction in bacterial surrogates over extended use periods and over a wide range of water quality characteristics, including those representing typical drinking water sources in Cambodia; (ii) that laboratory and field performance of filters would not differ appreciably with respect to microbial reduction; and (iii) that filters would maintain effectiveness through extended testing (greater than 500 l throughput) in both the laboratory and *in situ*.

1.2.1.2 Study overview: objective 1

Silver and iron oxide amendments, thought to increase microbiological effectiveness, have an unknown impact on the reduction of microbes in water treated by ceramic filters. Therefore, laboratory studies focused on the performance of the CWP as currently produced in Cambodia with $AgNO_3$ amendments (referred to in this study as the CWP1), a version of this filter supplemented with $AgNO_3$ and iron oxides (the CWP2), and an additional test filter without iron oxide or silver amendments (the CWP3). Laboratory experiments on the effectiveness of all three filters in the laboratory against *E. coli* and MS2 were followed by an 18-week field study of *E. coli* reduction in CWP1 and CWP2 filters in 120 households in the rural/peri-urban village of Prek Thmey, Cambodia. Performance against *E. coli* in the laboratory using spiked environmental waters was compared with field reductions. Field performance of filters was also compared with boiling, as the most prevalent method for water treatment at the household level in Cambodia.

1.2.2 Objective 2

The second objective was to evaluate the health impacts of the CWP1 and CWP2 filters in field use in a Cambodian village. Reduction of diarrheal diseases in all people and in children under five years of age were the principal outcomes of interest.

1.2.2.1 Hypothesis: objective 2

The study hypothesis was that in households using the ceramic filters (of either type), the diarrheal disease prevalence proportion in the intervention groups would be ≥20% less than in control households (without access to a filter). The bases for this detectible level of diarrhea reduction were the meta-analyses by Fewtrell *et al.* (2005) and Clasen *et al.* (2006a; 2007), which concluded that POU water treatment interventions can substantially reduce diarrheal disease in users versus non-users, by a mean of approximately 30 - 40%.

1.2.2.2 Study overview: objective 2

The study design was a randomized controlled trial, a rigorous epidemiological method for the assessment of health impacts of drinking water interventions (NRC 2004). After collection of baseline data (four weeks), participating households in a rural Cambodian village in Kandal Province were randomly assigned to one of three groups of 60 households: those receiving the currently produced filter (CWP1), those receiving an alternative filter design (CWP2), and those receiving no filter (control). Sample size calculations indicated that groups of 50 households were needed to detect a 20% reduction in diarrheal disease with 80% power, with nine post-baseline follow up visits. Households were followed for 18 weeks post-baseline with bi-weekly follow up to gather data on differences in proportions experiencing diarrheal illness over time by study group, controlling for clustering. Detailed data on hygiene, sanitation, demographics, water use practices, and other potential covariates were collected and used to examine potential associations with the disease outcomes. Exposure variables were presence of the intervention (either CWP1 or CWP2), water quality measures (e.g., *E. coli*/100 ml in household drinking water), and other WSH-related cofactors such as access to sanitation and hygiene behaviors. Measured health data were diarrheal disease for each individual in the previous 7 days and bloody diarrhea in the previous 7 days in individuals of all ages and in children under 5 years of age (0-48 months at the start of the study). A Poisson extension of generalized estimating equations (GEE) was used to produce estimates of effect reported as prevalence proportion ratios and incidence rate ratios between study groups, adjusted for clustering within households and within individuals over time. Pooled and stratified longitudinal prevalence proportion ratios were reported for risk of diarrheal diseases in groups by exposure status. Confounders were identified and adjusted for where appropriate based on an *a priori* 10% change-in-estimate criterion.

1.2.3 Objective 3

The third objective was to evaluate continued use, continued microbiological effectiveness, and associated health impacts of the CWP filter after up to nearly four years of use (0 – 44 months) in households in three provinces of rural Cambodia.

1.2.3.1 Hypothesis: objective 3

The study hypothesis was that the CWP as currently produced would continue to be used effectively in households in rural Cambodia beyond initial intervention programs, and that use of the intervention would be associated with improved household water quality and a reduction in diarrheal disease among users against a matched control group of households that never had filters.

1.2.3.2 Study overview: objective 3

The hypothesis was tested using data collected on Cambodian CWP implementations undertaken by local NGOs in Cambodia from 2002 until 2006. Data on continued use of the filters, diarrheal disease prevalence, microbiological performance, and important covariates were gathered to evaluate continued effectiveness and use *in situ* in Kandal, Kampong Chhnang, and Pursat provinces in Cambodia. The study was carried out in three parts: (i) a cross-sectional study of households that originally received filters to determine uptake and use proportions, as well as factors associated with successful adoption; (ii) a water quality assessment in 80 households successfully using the filters (from part i) to determine the microbiological effectiveness of the filters in treating household water, comparing treated and untreated household drinking water; and

(iii) a longitudinal health study that compared diarrheal disease outcomes in 80 households using the filters successfully to 80 control households (without filters). Control households were matched by drinking water source, socio-economic criteria, demographic data, and geographical proximity. Water quality data were collected for control households as well, including stored, boiled water samples, if available.

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

An estimated 1.8 million people die every year from diarrheal diseases, less than AIDS (2.8 million) but more than tuberculosis (1.6 million) and malaria (1.3 million) (WHO 2004). The majority of deaths are associated with diarrhea among children under five years of age in developing countries, who are more susceptible to malnutrition, dehydration, or other secondary effects associated with these infections (WHO 2004). Taken together, diarrheal diseases are the third highest cause of illness worldwide and the third highest cause of death in children worldwide (WHO 2004). Most diarrheal illness is associated with unsafe water, sanitation, and hygiene (Prüss-Üstün *et al.* 2004). Prüss *et al.* (2002) estimated that 4.0% of all deaths and 5.7% of the global disease burden are attributable to inadequate water, sanitation, and hygiene, including diarrheal diseases and other water-related diseases such as ascariasis and schistosomiasis, claiming 4.2% of disability-adjusted-life years (61.9 million) worldwide (WHO 2004). The study of human health risks due to WSH-related pathogen exposure has been central to the field of environmental health for over 150 years (Snow 1855), although the current global burden of diarrheal disease suggests there is still progress to be made.

An unknown percentage of the diarrheal disease burden is due solely to unsafe drinking water, since the viral, bacterial, and parasitic microbes causing diarrheal disease may also be transmitted through contaminated food, hands, fomites, or other routes (Wagner and Lanoix 1958). Drinking water quality, however, does play an important role in the risk of diarrheal diseases in humans and access to safe water is a major determinant of diarrheal disease outcomes. Diarrheagenic organisms generally originate in fecal matter and are transmitted through the fecal-oral route of infection (Curtis *et al.* 2000). Traditionally, among the most serious waterborne risks to public health have been the bacteria *Shigella* spp. (bacterial dysentery), *Vibrio cholerae* (cholera), and *Salmonella* spp. (typhoid, paratyphoid fever). Although these have mostly been eliminated from the developed world through advances in drinking water treatment, sanitation, and hygiene (Mackenbach 2007), they and other emerging and rëmerging pathogens continue to compromise water quality, and thus public health, in the less developed countries.

2.2 Summits, targets, and initiatives

The 1980s were declared the International Drinking Water and Sanitation Decade (IDWSD) by the United Nations General Assembly, a response to the Mar del Plata Action Plan produced at the 1977 United Nations Water Conference (UN 1992). The Mar del Plata Action Plan proposed that "all peoples, whatever their stage of development and their social and economic conditions, have the right to have access to drinking water in quantities and of a quality equal to their basic needs" (UN 1992). The IDWSD highlighted the problems of access which have always plagued developing countries but which have received increasingly widespread exposure from the 1960s (POST 2002). In response to the IDWSD goal of universal access to water and sanitation, the 1980s saw an increase in the number of large, supply-oriented development projects that eventually provided access to many in the developing world (UN 1992, 18.5.d). Despite progress made during this decade (1981-1990), increases in access to adequate supplies of drinking water only just matched increases in population (estimated at 750 million), leaving much work yet to be done (Mintz *et al.* 2001). The 1992 United Nations Conference on Environment and Development (UNCED) or "Earth Summit" in Rio de Janeiro reiterated the goal of universal access to clean water and sanitation in its principal document, Agenda 21 (UN 1992, 18.5d). The UN Millennium Declaration (2000) expressed the commitment of member states to “halve by the year 2015 the proportion of people…who are unable to reach or to afford safe drinking water" (UN 2000). The international commitment to this goal was affirmed at Johannesburg in 2002 (UN 2002). The year 2003 was declared the International Year of Freshwater by the United Nations. At its 58th session, the United Nations General Assembly adopted a draft resolution, without a vote (A/RES/58/217), proclaiming 2005 to 2015 as the International Decade for Action – Water for Life. This declaration restates the commitment of the international community to honor water and sanitation targets laid out previously in *Agenda 21*, the 2000 Millennium Development Goals, and the Johannesburg Plan of Implementation adopted at the of the World Summit of Sustainable Development in August 2002. The stated goal of the "Water for Life Decade” is “a greater focus on water-related issues, with emphasis on women as managers of water to help to achieve internationally agreed water-related goals”.

These and similar statements by the international community suggest the existence of broad political will for increasing access to safe drinking water. The extent to which this will is translated into action at the national and local levels, however, is the critical issue (Gleick 1998). Meeting the ambitious international goals for provision of safe water will require greater investment than that currently underway, especially given the projected one-third increase in the world's population by 2050 (Short 2002). In 2003 it was estimated that reaching the Millennium Goals would require providing access to safe water for 125,000 people per day every day for the 12 remaining years until 2015 (WQHC 2003). Because this lack of access to safe water is associated with a massive burden of disease, the World Health Organization (WHO) and others are eager to explore low-cost solutions for safe drinking water access, including decentralized technologies that can improve water quality post-source. It is clear that innovative solutions are needed to increase safe water and sanitation coverage, although the best strategies for doing so are widely debated.

2.3 Waterborne disease

2.3.1 Types of water-related disease

Unsafe water, sanitation, and hygiene are associated with a wide range of infectious diseases. Water-related infections may be broadly classified into four categories by environmental transmission route: water-borne, water-washed, water-based, and water-related (Table 2.1). This typology is commonly used by engineers and public health workers in identifying appropriate measures in interventions (Bradley 1977; Cairncross and Feachem 1993). Water-borne infections are directly transferred to an individual from ingested food or drink that is contaminated by human or animal waste carrying pathogens. This classification includes typhoid fever, cholera, hepatitis A virus (HAV), hepatitis E virus (HEV), and infections of *Shigella* spp and *E. coli* 0157:H7, among others (WHO 2006). Water-borne diseases are best prevented by improvements in microbiological water quality and prevention of casual use of unimproved sources

(Bradley 1977). Water-washed infections are the result of an inadequate supply of water for hygiene, facilitating the fecal-oral route of infection or transmission from one person to another (Gleeson and Gray 1997). Scabies, trachoma, and bacillary dysentery are examples (Bradley 1977). Water-washed diseases also include the water-borne diseases, since greater access to water provides for potentially better hygiene and more frequent hand washing, reducing the risk of disease (Curtis *et al.* 2000). Water-based infections are classified as those transmitted by contact with water that provides habitat for human parasites during some part of their life cycle. Disease is contracted either by direct skin contact or ingestion of a parasite or intermediate host living in the water. For example, schistosomes and other trematode parasites spend part of their life cycles in host organisms living in water. Schistosomiasis (bilharziasis) is caused in humans by the larval stage (*cercariae*) of the schistosome, which is transferred from infected snails to skin in contact with water (WHO 2006). Water-related diseases are those carried by organisms that breed in water or bite near water. Examples are the *Anopheles* mosquito, which carries malaria, and the *Aedes* mosquitoes that carry the viruses causing dengue and yellow fever (Gleeson and Gray 1997).

Category	*Examples*	*Relevant water improvements*	*Appropriate measures*
Water-borne	Typhoid, cholera, hepatitis	Microbiological improvements and protection of water from recontamination	Improve drinking water quality, decrease use of unsafe water sources, safely store water in the home to prevent recontamination
Water-washed	Scabies, trachoma, bacillary dysentery	Increase water supply	Improve availability and accessibility of water for hygiene, improve hygiene in other ways
Water-based	Schistosomiasis, dracunculiasis	Protection of user and/or source	Decrease need for water contact, reduce surface water contact, control vector population, reduce surface water contamination
Water-related	Malaria, sleeping sickness, dengue and yellow fever	Piped water supply, protected wells, sealed water storage	Improve surface water management, control breeding sites, control access to breeding sites, use mosquito netting and other interventions

Table 2.1. Classification of infectious diseases related to water and sanitation. Adapted from Bradley 1977, Storeygard 2002, Gleeson and Gray 1997, Cairncross and Feachem 1993.

2.3.2 Waterborne pathogens

Waterborne infectious diseases are caused by pathogenic bacteria, viruses, protozoa, or other parasites in water. Traditionally, among the most serious waterborne threats to public health in temperate regions have been *Shigella* (causing bacterial dysentery), *Vibrio cholerae* (cholera), and *Salmonella* (typhoid, paratyphoid). Although these have mostly been eliminated from the more developed world through appropriate water, sanitation, and hygiene improvements, these and other bacterial pathogens continue to compromise water quality and public health in the less developed countries (Gleeson and Gray 1997). Viral pathogens are also increasingly recognized as important agents of diarrheal illness worldwide. Norovirus, rotavirus, hepatitis A and E viruses, and enteroviruses are all responsible for waterborne disease outbreaks. Parasites such as the protozoa *Giardia intestinalis* and *Cryptosporidium parvum* continue to cause disease in developed and developing countries and are increasingly identified as etiologic agents in outbreaks of gastroenteritis. Other intestinal parasites, such as nematodes and cestodes (hookworm and tapeworm), may be transmitted through drinking water, although this is less common.

Diarrheagenic organisms generally originate in fecal matter and are transmitted through the fecal-oral route of infection (Curtis *et al.* 2000). Drinking water is only one possible means of infection; the fecal-oral route also includes transmission via soiled food, hands, clothing, or utensils (ibid., Wagner and Lanoix 1958). These routes are especially important where sanitation and hygiene are inadequate (WHO 2006).

2.3.3 Diarrheal diseases

The word "diarrhea" is derived from the ancient Greek for "leakage" (διαρροή, literally "flowing through", Schiller 2002). Diarrheal disease is characterized by lower than normal stool consistency and greater than normal stool frequency. Some definitions also include a third component of increased stool weight (e.g., > 200 g/24 hr) (ibid.). A common definition is "three or more loose or watery stools within a 24 hour period" although in practice this is variously defined by patients and health care workers.

Diarrheal illnesses range from acute syndromes such as cholera and dysentery to extended or chronic illnesses like typhoid fever and Brainerd diarrhea. Typical symptoms may vary with the age, immune system health, nutritional status, and other characteristics of the individual, and with the etiologic agent or agents responsible for infection. Some causes of infectious diarrhea may result in serious long-term sequelae such as hemolytic uremic syndrome, Guillain-Barré syndrome, and malnutrition (leading to stunted growth and greater susceptibility to disease). In otherwise healthy, immunocompetent individuals, cases may be self limiting and usually resolve within a few days. In chronic infections, symptoms may persist for weeks, with serious risks to health, especially in children, as a result of severe dehydration and other effects. Malnutrition increases both the susceptibility and severity of infection, representing both a cause and effect of diarrheal disease (Gadewar and Fasano 2005). Dysentery, or bloody diarrhea, causes about 20% of deaths associated with these infections, with 35% of deaths attributable to non-dysenteric acute diarrhea and 45% attributable to persistent diarrhea (Blaser 1995; Black 1993; Clasen *et al.* 2006a).

The effects of exposure to pathogens are unevenly distributed in populations, with the greater disease burden carried by the young, elderly, pregnant, or immuno-deficient (WHO 2006). Children are particularly susceptible to diarrheal disease and are more likely to die from the effects. According to Bartram (2003), children bear 68% of the global diarrheal disease burden, with 17% of all deaths in children under five years of age attributable to these diseases and their sequelae (UN 2005; cited in Clasen 2006a). Coinfection with HIV/AIDS increases chronic illness and mortality associated with diarrheal diseases (Grant *et al.* 1997; Colebunders *et al.* 1987; Brink *et al.* 2002; Kaplan *et al.* 1996; and Hayes *et al.* 2003). At the global level, a disproportionately high level of risk of water related disease is borne by the world's poor; approximately half of all people living in developing countries at any given time has a health problem caused by a lack of water and sanitation (Moszynski 2006). The CDC estimates that greater than 2 billion people are at high risk for diarrheal infection in the developing world, due to unsafe water, sanitation, and hygiene (CDC 2003).

Oral rehydration therapy (ORT), mineral supplements (e.g., zinc), and treatment with probiotics (e.g., *Lactobacillus*) and antibiotics are common treatments worldwide for acute diarrheal diseases (Sur and Bhattacharya 2006). Access to health care or appropriate treatment is often not common in the developing world, however. Some advocate the development of vaccines to common diarrheal disease agents as an alternative to increasing water, sanitation, and hygiene coverage, improvements that may be seen as "impractical" (Gadewar and Fasano 2005; Nataro 2004). Others identify key treatment and vaccine options as complementary efforts to increasing access to safe water, sanitation, and hygiene (Thapar and Sanderson 2004). Sanitation (including improved sewage disposal and clean water supply systems) has been voted the most important medical milestone since 1840 (over anesthesia, antibiotics, and vaccines) in a poll conducted by the British Medical Journal (BMJ) (Mackenbach 2007), largely due to the substantial reduction in infectious diseases (e.g., cholera and other diarrheal diseases) experienced by populations having access to improved water and sanitation.

2.3.4 Diarrhea and drinking water

Improved drinking water quality, sanitation, and hygiene practices are all widely believed to be important in reducing the burden of diarrheal disease, although the relative importance of these factors is widely debated in the literature (e.g. Tumwine *et al.* 2002; Macy and Quick 2002; Curtis *et al.* 2000; Esrey *et al.* 1991). Up to 30% of the global diarrheal disease burden may be associated with consumption of unsafe drinking water (Macy and Quick 2002). That each of these factors is important in achieving a reduction in the water-related disease burden is widely acknowledged (WHO 2006). But given the reality of scarce international funding and widespread pressure on obtaining the maximum reduction of disease per dollar spent, it is important to identify which strategies and combinations of strategies are most efficient in achieving the goals set by the international community. Drinking water quality is now increasingly recognized as being as important as other water, sanitation, and hygiene factors in determining diarrheal disease risk (Clasen and Cairncross 2004; Fewtrell *et al.* 2005; Clasen *et al.* 2006a; Clasen *et al.* 2007). Previous reviews have emphasized the importance of water supply, sanitation, and hygiene improvements over drinking water quality in the reduction of diarrheal disease (Young and Briscoe 1988; Esrey *et al.* 1988; Esrey *et al.* 1991; Cairncross 1992).

2.4 Access to safe water

Between one and two billion people lack adequate access to improved water sources and a greater number lack access to microbiologically safe water as defined by the Guidelines for Drinking Water Quality (WHO 2006; WHO 2004; Tumwine 2002). Thus this basic human need and, according to the United Nations, basic human right, remains beyond the reach of between one-sixth and one-third of the world's population and a much higher percentage of the world's poor (UN 1992; WHO 2003; Short 2002; Tumwine 2002). Inadequate access to safe drinking water contributes to the staggering burden of diarrheal diseases worldwide. Drinking contaminated water can also reduce personal productive time by an estimated 10%, with widespread economic effects (UN 1992). Over 440 million school days are missed annually due to WSH-related illnesses (Moszynski 2006). Problems associated with poor drinking water quality are significant barriers to development, both human and economic.

The United Nations' Millennium Development Goals (MDG) address the desperate need to provide safe drinking water to those who need it, which currently includes 40% of the population in Africa, 19% in Asia and 15% in Latin America and the Caribbean. The problem is becoming more serious as the urban populations of Africa and Asia may double in 25 years, while those of Latin America and the Caribbean are expected to increase by 50%. The MDG target of halving the population without access to safe drinking water by 2015 is sorely off pace for some areas of the world, notably sub-Saharan Africa (Anyangwe *et al.* 2006), but expanded access to basic needs such as clean water and adequate sanitation remains an important long-term goal.

2.5 Point-of-use water treatment interventions

Waterborne diseases are preventable through effective control measures (Clasen *et al.* 2007; Fewtrell *et al.* 2005). The emergence of POU water treatment technology as a strategy for safe water provision at the household level may have significant health impacts in populations lacking the means to secure safe drinking water. With the formation of the International Network to Promote Household Water Treatment and Safe Storage (INPHWTSS) and its acceptance at the Third World Water Forum in Kyoto (2003), broad-based international attention has been focused on this strategy. It is expected that the use of POU water treatment technologies will contribute to accelerated health gains from improved access to clean, safe drinking water (Sobsey 2002).

Drinking water quality improvements, such as effective household-scale water treatment, can have a significant health impact, although the relationship between measured indicators of water quality (such as *E. coli*) are often associated only tenuously with measured diarrheal disease outcomes (Jensen *et al.* 2004; Moe *et al.* 1991). Recent studies have shown that reductions in diarrheal disease are attainable through household-scale drinking water treatment (Clasen *et al.* 2004; Colwell *et al.* 2003; Sobsey *et al.* 2003; Conroy *et al.* 200l), leading to greater interest in these interventions worldwide (Clasen and Cairncross 2004). Previous reviews of the impacts of water supply, water treatment, sanitation, and hygiene interventions on diarrheal disease concluded that hygiene and sanitation, followed by water supply and water quality, were the most important interventions to prevent diarrheal disease in less developed countries (Esrey *et al.* 1985, 1986, and 1991). In these seminal reviews of field trials of water and sanitation interventions, results indicated that hygiene interventions reduced diarrheal disease by 33%, sanitation 22%, water supply 22%, water quality 17%, and multiple interventions 20%. However, household-based water treatment or other household water quality interventions were not included in these analyses. Quality of water in the home, however, has been shown to be critical to health, since this is the water that is usually used for drinking (Jensen *et al.* 2002). The findings of two recent meta-analyses show a much stronger protective effect for water quality interventions at the household level on diarrheal disease outcomes (Table 2.2; Fewtrell *et al.* 2005; Clasen *et al.* 2006a). The conventional wisdom that water quality interventions, while part of the solution, were at best a component of larger interventions including hygiene education, sanitation, and an improved water supply, with the most important of these being hygiene (Curtis and Cairncross 2003), has now been refined to recognize the importance of household drinking water quality as a critical exposure variable related to diarrheal disease outcomes in developing countries.

A further meta-analysis and systematic review undertaken by Clasen *et al.* (2007) incorporated 33 trials on household-based interventions, including point-of-use chlorination, filtration, solar disinfection, combined flocculation and disinfection, and improved storage. Results indicate that these interventions reduce diarrheal disease in people of all ages (longitudinal prevalence proportion ratio = 0.70, 95% CI 0.56 to 0.88, 9 trials) and in children under 5 years of age (longitudinal prevalence proportion ratio = 0.76, 95% CI 0.66 to 0.88, 9 trials). Further analyses were performed within specific intervention categories and results were stratified by outcome measure (odds ratio, longitudinal prevalence proportion ratio, rate ratio, risk ratio). Household-based interventions were more effective than water quality interventions at the source (ibid; Clasen *et al.* 2006a); consistent use of the technology was associated with greater effectiveness; and evidence did not support the conclusion that technologies have a greater effect when bundled with other interventions.

An important finding of the Clasen *et al.* review (2006a, 2007) is that only four of 22 randomized controlled trials included in the analysis were blinded (using a placebo group), and no blinded trial showed a protective effect against diarrheal disease in users. This fact highlights the primary deficiency of the literature constituting the evidence base for water quality interventions that are intended to reduce diarrheal disease.

Type of intervention	*Number of studies*	*Rate ratio pooled effect (95% CI)*
Hygiene	11	0.63 (0.52 – 0.77)
Excluding poor quality studies	8	0.55 (0.40 – 0.75)
Handwashing	5	0.56 (0.33 – 0.93)
Education	6	0.72 (0.63 – 0.83)
Sanitation	2	0.68 (0.53 – 0.87)
Water supply	6	0.75 (0.62 – 0.91)
Diarrhea only	4	1.03 (0.73 – 1.46)
Household connection	2	0.90 (0.43 – 1.93)
Standpipe or community connection	3	0.94 (0.65 – 1.35)
Water quality	15	0.69 (0.53 – 0.89)
Source treatment only	3	0.89 (0.42 – 1.90)
Household treatment only	12	*0.65 (0.48 – 0.88)*
Household treatment		
excluding poor quality studies	8	*0.61 (0.46 – 0.81)*
rural location	6	*0.61 (0.39 – 0.94)*
urban/periurban location	5	0.86 (0.57 – 1.28)
urban/periurban excl. Sathe *et al.* 1996	4	0.74 (0.65 – 0.85)
Multiple (combinations of the above)	5	0.67 (0.59 – 0.76)

Table 2.2. Results of meta-analysis of effects of water-related interventions on diarrhea from Fewtrell *et al.* (2005). CI = confidence interval.

2.5.1 The roles of point-of-use (POU) water treatment

Centralized water treatment and delivery systems have many advantages, including significant economies of scale over decentralized systems and potential ease of access to water in quantity. Traditional strategies for provision of access to safe drinking water are not, however, meeting the needs of the 1-2 billion people who lack access to improved drinking water sources and the potentially much greater number without access to microbiologically safe water. Piped supplies require high capital investment, a concentrated population large enough to justify construction, a suitable raw water source of high quality or centralized treatment, and ongoing operation and maintenance costs requiring fees of users. Inadequate treatment and aging or compromised distribution systems are the norm in developing countries; these systems do not generally deliver water of high quality (Luby *et al.* 2000; Lykins *et al.* 1994; Reller *et al.* 2001; Weber et al 1994; Swerdlow *et al.* 1992). Urban municipal supply systems in the developing world often require some point-of-use treatment, either through boiling or an alternative like ceramic microfiltration (Gleeson and Gray 1997, 161). POU systems may find a great deal of use in more developed countries as well, either in places not served by a municipal system or in places where doubts exist as to the quality of the public water supply (Lykins *et al.* 1994). They can also be used to improve aesthetic qualities of otherwise safe water that meets regulation (ibid.). Often, chlorination at the plant does not guarantee sufficient residual chlorine at all points in the distribution system, as was the case at Guayaquil, Ecuador (Weber et al 1994), in a study from Madagascar (Reller *et al.* 2001), and one from Peru (Swerdlow *et al.* 1992). Chlorine is also not suitable for use against encysted protozoa such as *Giardia* and *Cryptosporidium*, two common waterborne pathogens (Warwick 2002). The reasons for failures in municipal systems are contamination of source water which is passed on to users with insufficient or no treatment, inadequate chlorination to maintain chlorine residual to the entire system, contamination in transit through poorly maintained distribution systems and problems with illicit connections, and low or intermittent system pressure allowing back-siphonage of contaminating material into the system (ibid.).

Alternatives to the traditional models of safe water provision are sorely needed in the developing world. In addition to improved access to sufficient water quantity, water quality improvements at the "point of use" (POU), usually at the household level, are critical to protecting public health. With the formation of the International Network to Promote Safe Household Water Treatment and Storage at the Third World Water Forum

(Kyoto, March 2003), broad-based international attention has been focused on this strategy. Point of use (POU) water treatment technologies are any of a range of devices or methods employed for the purposes of treating water in the home or at point of use in other settings. These are also known as household water treatment (HWT) or, when included with technologies or methods for safely storing drinking water, household water treatment and safe storage (HWTS) . Most current POU technologies are intended to reduce microbial pathogens, although some also reduce chemical and radiological contaminants. Taken together, POU systems comprise a range of intermediate technologies (Schumacher 1973) with the goal of rapidly increasing access to clean water at the lowest possible cost to individuals and communities. These systems are increasingly touted as practical solutions to problems of degraded drinking water quality in the developing world, where collecting water outside the home and storing it for household use is the norm and generally unsafe water is delivered via piped supplies where it is available (Chaudhuri and Sattar 1990; Sobsey 2006). The use of POU systems may contribute to "accelerated health gains" from improved access to clean drinking water where centralized water treatment and delivery systems are unavailable or inadequate (Sobsey 2002).

Household-based drinking water treatment, because it does not deliver water through a pipe, cannot represent a method for provision of safe or "improved" water under the definitions in use by the Joint Monitoring Programme (WHO and UNICEF 2005), and thus may not contribute to Goal 7, target 10 of the MDGs as currently defined, although POU water treatment is gaining recognition as a potential method of providing access to safe drinking water (UN 2005). While both quantity and quality of water have significant public health impacts (Fewtrell *et al.* 2005; Clasen *et al.* 2006a), a greater focus on making water safe to drink is needed for WSH development to significantly reduce the diarrheal disease burden in developing countries (Sobsey 2002; Sobsey 2006).

Ideally, POU systems can also safeguard against stored water contamination in the home through unsafe water handling practices, known to be a major cause of degraded drinking water quality (Clasen and Bastable 2003; Jensen *et al.* 2002; Momba and Kaleni 2002; Brick *et al.* 2004; Mintz *et al.* 1995; Wright *et al.* 2004). For this reason safe storage is an important aspect of some technologies used for drinking water treatment or safe storage containers may be used as a stand-alone technology for protecting water quality where the main source of contamination is improper handling (Mintz *et al.* 1995; Clasen *et al.* 2004; Roberts *et al.* 2001). Devices that store water safely prevent users from dipping hands or other potentially contaminated objects into the water container, acts that may introduce disease causing microbes. Safe storage containers thus usually have a narrow mouth (so that water is obtained by pouring, not dipping) or a tap that dispenses the stored water into a cup for drinking. While there are ways around safe water storage systems, the concept of using design to prevent recontamination in the home is a good one and this strategy has been linked to gains in health.

Household water treatment may be especially critical for use in populations with greater susceptibility to waterborne infectious diseases, since those with HIV/AIDS or the malnourished are more susceptible to chronic morbidity and mortality as a result of diarrheal disease (Lule *et al.* 2005; Gadewar and Fasano 2005). Vulnerable populations are growing as HIV/AIDS and other factors increase susceptibility to waterborne infections (Sattar *et al.* 1999).

Point-of-use treatment is also suited to crisis interventions where emergency supplies of potable water are needed (Curtis *et al.* 2000; Mong *et al.* 2001; Clasen 2005; WHO 2005), although in practice emergency implementation is not straightforward (Clasen and Boisson 2006). Breakdowns in water supply systems can occur as a result of natural disasters, war and human conflict, or simply inadequate maintenance of infrastructure (Curtis *et al.* 2000). POU treatment can also be used in temporary settlements such as refugee camps or shelters (Roberts *et al.* 2001; WHO 2006; Doocy and Burnham 2006).

2.5.2 POU water treatment: technologies

Key reviews of POU water treatment and safe storage technologies have advanced the current knowledge about practical aspects of these interventions and their application in developed and developing countries (Sobsey 2002; Lantagne *et al.* 2006; HIP 2006; IRC 2005). Physical methods for small-scale water treatment include boiling, heating (using fuel and solar), filtering, settling, and ultraviolet (UV) radiation (solar or ultra violet lamps). Chemical methods include coagulation-flocculation and precipitation, ion exchange, chemical disinfection with germicidal agents (primarily chlorine), and adsorption. Combinations of these methods simultaneously or sequentially often yield promising results, for example coagulation combined with disinfection (Souter 2003). Other combinations or multiple barriers are media filtration followed by chemical disinfection, media filtration followed by membrane filtration, or composite filtration combined with chemical disinfection (Clasen *et al.* 2006c). These and other reviews of technologies have suggested that success of interventions is highly context-specific, with no one technology or method representing a universal best solution. Availability of materials, quality of raw water available, cultural factors and preferences, or cost may determine where each of these is most suited to POU water treatment applications in developing countries (Sobsey 2002).

2.5.2.1 Existing standards for microbiological effectiveness

Water treatment technology verification protocols for microbiological performance, often referred to as ETVs after the US EPA's *Environmental Technology Verification* program, exist in the United States and some other countries. Current standards for point-of-use water treatment for the United States specify a minimum 6 $\log_{10}$ (99.9999%) reduction in bacteria, 4 $\log_{10}$ (99.99%) reduction in viruses, and 3 $\log_{10}$ (99.9%) reduction in protozoan parasites demonstrated over a range of conditions and for prescribed volumes of water treated using specific test microbes (USEPA 1987; NSF 2003).

All developed country protocols are highly prescriptive and are often intended to independently verify performance claims made by a manufacturer that may be linked to country-specific standards, not necessarily derived from health-based targets as articulated in the WHO *Guidelines for Drinking Water Quality* (WHO 2006). They typically specify the test pathogens or chemicals, test (challenge) water quality, frequency and duration of challenging the technology with contaminant-laden water, minimum contaminant reduction requirements, and other procedural and performance specifications. Current protocols have the advantage of being universal, thus enabling direct comparisons to be made among a wide range of technologies. However, the protocols were developed principally for devices and unit processes to be used in developed countries and are less suited to conditions and POU water treatment and storage practices in developing countries. No international standards yet exist for the verification of household water treatment technologies, although WHO-led efforts to establish performance and testing guidelines based on the risk-based framework articulated in the Guidelines for Drinking Water Quality (WHO 2006) are underway. Such guidelines will need to be flexible because of varying laboratory capabilities, resources, and implementation contexts; emerging and evolving technologies; and the goal of encouraging incremental improvements in performance. The availability of new or modified protocols, material and methods for laboratory verification will enable manufacturers, regulators and implementers to ensure effectiveness of candidate POU technologies while providing flexibility and consideration of local conditions and needs.

2.5.2.2 Filtration technologies

POU filtration technologies include cloth or fiber filters, membrane filters, porous ceramic filters, and granular media filters (Table 2.3). These filters reduce microbes by a combination of physical and chemical (and, in some cases, biological) processes including physical straining, sedimentation, and adsorption. Filtration technologies are finding increasing application in developing countries where chemical disinfection or boiling may not always be practical or effective (Colwell *et al.* 2003).

Traditional membrane technology is generally expensive and therefore largely unknown for small scale drinking water treatment in developing countries, although reverse osmosis and other membrane technologies are common in developed countries (Payment *et al.* 1991; Hörman *et al.* 2004) and may be used by travelers to developing countries (Backer 2002). These advanced filters may include composite filters that employ several methods for reduction of microbes in water. Some low-cost applications of these types of filters have been in development and may have a role to play in the future of household water treatment in developing countries.

Cloth filters, such as those of sari cloth, have been recommended for reducing *Vibrio cholerae* in water when these are associated with copepods or other eukaryotes in water (Colwell *et al.* 2003; Huo *et al.* 1996). These cloths will not significantly retain dispersed bacteria not associated with copepods, other crustaceans, suspended sediment, or large eukaryotes because the pores of the cloth fabric (>20 μm) are not sufficiently small to exclude bacteria, but where appropriate these filters can have significant health impacts. Colwell *et al.* 2003 reported a 48% reduction in cholera associated with use of the filters over a 35 month trial that included 65 villages in rural Bangladesh and approximately 133,000 participants. Cloth filters have also been critical interventions in guinea worm (dracunculiasis) eradication programs (Aikhomu *et al.* 2000; Olsen *et al.* 1997).

Granular media filters include those containing sand, diatomaceous earth, or others using discrete particles as packed beds or layers of surfaces over or through which water is passed. Other granular media filters are biologically active because they develop layers of microbes and their associated exopolymers on the surface of or within the granular medium matrix. This biologically active layer, called the *schmutzdecke* in conventional slow sand filters, retains microbes and often leads to their inactivation and biodegradation. A household-scale filter with a biologically active surface layer and that can be dosed intermittently with water has been developed called the BioSand filter, which is an intermittently operated slow sand filter (IOSSF) (Stauber *et al.* 2006). The BioSand system has been the subject of several studies (Duke *et al.* 2006a; Stauber *et al.* 2006).

Treatment process	*Pathogen group*	*Baseline removal (LRV[a])[b]*	*Max. removal (LRV)[c]*	*Notes*	*References*
Membrane Filtration	Bacteria Viruses Protozoa	2+ 0+ 2+	6+ 4+ 6+	Varies with membrane pore size (micro-, ultra-, nano- and RO filters), integrity of filter medium and filter seals and resistance to chemical and biological "grow through") degradation	Jacangelo *et al.* 1997; Hörman *et al.* 2004
Fiber and fabric filters (e.g., sari cloth filters)	Bacteria Viruses Protozoa	1 0 0	2 0 1	Particle- or plankton- association increases removal of microbes, notably *V. cholera*; protozoa >20 µm may be removed (*G. intestinalis* is 14 µm, *C. parvum* 3-5 µm); ineffective for viruses and dispersed bacteria	Colwell *et al.* 2003; Huo *et al.* 1996
Porous ceramic filtration	Bacteria Viruses Protozoa	2 0.5 4	6 4 6	Varies widely with pore size, pore structure, and tortuosity; flow rate; possibly with filter medium augmentation via silver or other chemical agents	Lantagne 2001a,b; Sobsey 2002; unpublished data
Intermittently operated slow sand filter (IOSSF)	Bacteria Viruses Protozoa	1 0.5 2	3 2 4	Varies with filter maturity, operating conditions, flow rate, pause time, grain size, filter bed contact time, and other factors; POU systems based on modifications of traditional slow sand filtration may differ in microbial removal from slow sand filtration	Hijnen *et al.* 2004; Timms *et al.* 1995; Stauber *et al.* 2006

a. Log_{10} reduction value, a commonly used measure of microbial reduction, computed as log_{10} (pre-treatment concentration) – log_{10} (post-treatment concentration).

b. Baseline reductions are those typically expected in actual field practice when done by relatively unskilled persons who apply the treatment to raw waters of average and varying quality in developing countries and where there are minimum facilities or supporting instruments to optimize treatment conditions and practices.

c. Maximum reductions are those possible when treatment is optimized by skilled operators who are supported with instrumentation and other tools to maintain the highest level of performance in waters of predictable and unchanging quality

Table 2.3. Estimates of baseline and maximum effectiveness of filter technologies against microbes in water, including porous ceramic filtration and other proposed POU filtration technologies.

2.6 Ceramic filters for drinking water treatment

Ceramic filtration is the use of porous ceramic (fired clay) to filter microbes or other contaminants from drinking water. Ceramic filtration for drinking water treatment has a long pedigree, having been used in various forms since antiquity; modern historical references to ceramic water "drip" filters with safe storage elements suggest they have been used widely for over 100 years in Latin America (García Márquez 1999, p109-110) and ceramic filters have been produced in Britain at least since 1850. Today, pore sizes can be made small enough to remove virtually all bacteria and protozoa by size exclusion, down to 0.2 μm, in the range referred to as microfiltration. Ceramic filters are also often enhanced with a variety of silver-containing microbiocidal amendments that are either painted onto the surface, impregnated into the ceramic matrix before or after firing, or applied to filter elements in other ways. Silver nitrate solutions or colloidal suspensions of silver are most often used for this purpose, a practice that began in the early 20th century to control the problem of bacterial growth in porcelain (ceramic) Pasteur household-scale water filters (Merriman 1906).

Ceramic filtration technology may be broadly divided into two categories: the relatively advanced technology of those filters made in more developed countries, which are made to exact specifications with considerable quality control and commensurate cost; and those made in developing countries, where there is some variation in effectiveness but which often employ local materials and expertise, producing a product that is relatively inexpensive and locally available. The principal example of the latter is the *Filtrón* project undertaken by Potters for Peace, an NGO that promotes the technology (Lantagne 2001a, 2001b). The filters have been the focus of increasing research during the 1990s and 2000s through partner organizations of the WHO International Network to Promote Household Water Treatment and Safe Storage.

Low cost ceramic filtration for drinking water treatment in developing countries is diverse, varying by overall design, production method, clay and other materials, quality assurance and quality control (QA/QC) procedures, burnout material, firing temperatures and methods, chemical (e.g., colloidal silver) amendments, and other characteristics (Lantagne 2001; Sobsey 2002; Cheesman 2003; Dies 2003). Because the design and available materials and methods vary widely from region to region, few generalities can be made about low cost ceramic filters as a whole. Also, effectiveness data for one ceramic filter design may not be representative of other systems, or even in some cases of separate batches of filters made at the same factory. Moreover, these technologies are in flux as NGOs and others work to test and improve the technologies to be more effective interventions for improving water quality at the point of use.

2.6.1 Local ceramic water filter technology

Locally produced ceramic filters have the advantages of being lightweight, portable, relatively inexpensive, and low-maintenance. Filters provide for removal of microorganisms from water by gravity filtration through porous ceramic, with typical flow rates of 1-3 l/hr. Used with a controlled access storage receptacle, water is safely stored to prevent recontamination. Unlike chemical or thermal disinfection, ceramic filters do not significantly change water taste or temperature and do reduce turbidity: aesthetic improvements that may be strong motivators for use of the technology to treat household water (Brown 2003; Roberts 2003; Clasen *et al.* 2004). Filters have functional stability in the sense that they have only one moving part (the tap) and require no external energy source (such as UV lamps) or consumables (such as chlorine packets, or media that must be regenerated or replaced). They have a potentially long useful life of 5+ years (Lantagne 2001b; Campbell 2005) with proper care and maintenance, although manufacturers and implementers may recommend regular replacement of the filter element every 1-2 years. The ceramic filter surface is regenerated through periodic scrubbing to reduce surface deposits that slow filtration rates. Therefore the useful life of a ceramic filter may be limited by the frequency of cleaning, and thus the quality of water being treated, and the thickness, since repeated cleaning will eventually degrade the filter element. Filter breakage, however, is more commonly cited as the primary reason for discontinued filter use, although breakage is associated with more frequent handling (including regular cleaning), highlighting the potential links between user behavior and filter longevity in household use. Costs of filters vary, but most retail in the US$5 – US$25 range. The CWP in Cambodia retails for under US$10 in 2007. Replacement filter elements cost US$2.50-$5.00 in Cambodia. Since filters can be made locally by the private sector, they can also provide a source of income in poor communities, although most production of the CWP-type filters worldwide to date is NGO-based.

2.6.2 Development of the ceramic water purifier (CWP)

With financial aid from the InterAmerican Development Bank, as part of a development and diffusion of intermediate technology program, ICAITI (the Instituto Centroamericano de Investigación y Technología Industrial, a research institute based in Guatemala) developed a prototype ceramic filter to be used for drinking water treatment in rural areas of Central America from 1981 (AFA Guatemala 1995). The filter design has been in development since then with the involvement of several NGOs in Latin America and around the world, with the NGO Potters for Peace (PfP) playing a key role in the diffusion of the technology since 1998. The PfP filter, called *Filtrón* in Latin America, the *C.T. Filtron* in Ghana, and the Ceramic Water Purifier (CWP) in Cambodia, is now produced in Nicaragua, El Salvador, Guatemala, Honduras, Cambodia, and Ghana. Current start-up projects (not producing filters in 2007) exist in Cuba, Colombia, Mexico, Bali, the Dominican Republic, Ecuador, Sri Lanka, Myanmar, Yemen, Kenya, Tanzania, and Benin (Lantagne 2007; Rivera 2007). Program success and implementation models vary widely between countries and there are no standardized production or quality control methods for the filters (Figure 2.1).

Figure 2.1. The ceramic water purifier (CWP) and porous ceramic pots stacked for drying, as manufactured by Resource Development International, Kandal Province, Cambodia. Porosity in the ceramic (< 1 μm and larger) is created by mixing finely ground rice husks into the clay, which combust in the firing process to leave behind pore spaces. Water passes through the porous ceramic filter element by gravity (capacity approximately 10 l) at 1-3 l/hr into the receiving container (20 l), where it is dispensed via a tap to prevent post-filtration contamination of the product water through dipping or other contact with soiled hands or vessels. Filters are treated with a $AgNO_3$ solution to reduce microbial recontamination of the filter and biofilm formation and increase microbiological effectiveness.

2.6.3 Microbiological effectiveness of low cost ceramic water filters

The reduction of microbial pathogens through treatment by ceramic filtration may involve one or more physical or chemical processes. Mechanisms may vary widely between filters and have not been adequately characterized. In the case of low-cost, locally-made filters, the pore size varies widely by ceramic material, burnout material, firing temperature, and other factors; filter void spaces tend to have a tortuous configuration (Fahlin 2003) that may contribute to increased microbial removal efficiency. Microbe or chemical interactions such as sorption with the filter's ceramic surface may also effect reductions of key contaminants. In the Potters for Peace (PfP) process, most commonly a colloidal silver solution is painted onto or used as a bath to soak ceramic filter elements. Silver nitrate is used to treat the CWPs produced by the NGO Resource Development International in Cambodia. These amendments are widely held to increase the microbiological effectiveness of the filter and to inhibit biological growth within the filter. Lantagne (2001a) provides a comprehensive overview of the use of silver amendments in the low-cost ceramic filters. Silver impregnation is also commonly found in commercially available ceramic filters available in the USA and Europe.

The evidence base for microbiological effectiveness of the ceramic water filters in the laboratory and in field use remains inadequate. Studies to date have been limited in scope, methodological rigor, and quality, often with little information about untreated versus treated water quality (matched pre- and post-treatment samples) and little information on analytical methods used, sample handling and processing, volume sampled, replicates, dilutions, incubation, detection limits, and other relevant information. Lantagne (2001a) provides a general review of early effectiveness studies on the filters as produced in Central America. No studies on low-cost ceramic filters have been published in the peer reviewed literature, although several studies have provided some evidence that links filter use to improvements in water quality at the point of use. Non-peer reviewed studies by Roberts (2003), Lantagne (2001a), Duke *et al.* (2006b), Val Halem (2006), Baide (2001), AFA Guatemala (1995), Mattelet (2006) and others have suggested that low-cost, PfP-type ceramic water filters do have the potential to provide microbiologically improved water to users as indicated by a reduction in surrogates for disease causing microbes. More work is needed, however, to adequately characterize the microbiological effectiveness of these interventions.

The proper use of drinking water treatment technology is as critical to its effectiveness as the technology itself (Draffin 1939). Limited presence/absence field microbiological effectiveness data (24 pre- and post-treatment samples) reported by Lantagne (2001b) indicated that field effectiveness against total coliforms, H_2S-producing bacteria, and *E. coli* was substantially less than in lab studies summarized earlier (Lantagne 2001a). A lower observed effectiveness under field use conditions has been reported elsewhere (Baumgartner 2006; Roberts 2003); lower reductions in the field suggest links between environmental factors or user behavior and technology effectiveness. In limited initial studies, Campbell (2005) and Lantagne (2001b) showed that filters can maintain effectiveness in field use for a long time (≥5 years); thus proper use can potentially ensure sustained access to microbiologically improved drinking water.

2.6.4 Health impacts associated with use of low cost ceramic filters

Some evidence for the intervention's ability to reduce diarrhea in users versus non-users exists in non-peer reviewed publications. Roberts (2003) reported that filter users reported approximately half the cases of diarrhea as a control group in a field study of approximately 100 households in Cambodia. In a Guatemalan study of the impacts of filter use and maternal health education on diarrheal disease among children under 5 years, there was a reported 53% reduction in diarrheal incidence due to filters alone, 65% reduction for filters used in conjunction with educational program, and 21% reduction for education alone over the two year study (24 follow up visits) including 1120 children in three regions (AFA Guatemala 1995). The filter used in this study was a predecessor of the Filtrón promoted by Potters for Peace, developed by ICAITI.

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CHAPTER 3: LABORATORY AND FIELD EFFECTIVENESS OF LOW-COST CERAMIC FILTERS FOR DRINKING WATER TREATMENT IN CAMBODIA

Abstract

Waterborne pathogens contribute to the global burden of human disease and drinking water quality is a major determinant of diarrheal disease burdens. Low-cost options for the treatment of drinking water at the household level are being explored by the Cambodian government and NGOs working in Cambodia, where 66% of the population lack access to improved drinking water sources and diarrheal diseases are the most prevalent cause of death in children under 5 years of age. The ceramic water purifier (CWP), a locally produced low-cost ceramic filter, is now being implemented by several NGOs and an estimated 100,000 people in the country now use them for drinking water treatment at the household level. This study presents results from laboratory and field-based testing of these CWPs for their ability to reduce coliphages and bacteria in drinking water sources in Cambodia. The effectiveness of three candidate filters were tested extensively in the laboratory for the reduction of bacterial and viral surrogates for waterborne pathogens using representative drinking water sources (rain water and surface water) spiked with test microbes. Filters were tested over a greater than 600 l total throughput. Two filters were then evaluated for field effectiveness in reducing microbes in household water in Prek Thmey, a rural/peri-urban village in Cambodia, over 18 weeks of use. Results indicate that filters are capable of reducing key microbes in the laboratory

and in field use conditions, with mean reductions of *E. coli* of approximately 99% and mean reduction of bacteriophages of 90-99%.

3.1 Introduction

The evidence base for microbiological effectiveness of the ceramic water filters in the laboratory and in field use remains limited, especially in the peer reviewed scientific literature. However, Roberts (2004), Lantagne (2001a), Duke *et al.* (2006), Val Halem (2006), Baide (2001), AFA Guatemala (1995), Mattelet (2006) and others have reported results that suggest low-cost, pot-style ceramic water filters do have the potential to provide microbiologically improved water to users as indicated by a reduction in indicators of fecal indicator or pathogenic microbes (Table 3.1). As summarized in Table 3.1, low cost ceramic filters have been shown to reduce bacteria by at least 3 $\log_{10}$ and protozoan parasites by at least 4 $\log_{10}$. However, viruses have been reduced typically by less than 1 $\log_{10}$. These results are consistent with the expected pore size of the filters being in the microporous range and therefore able to appreciably retain bacteria and protozoa but too large to retain viruses.

Previous studies (Clasen *et al.* 2004; Clasen *et al.* 2006) have shown candle-type ceramic filters made in richer countries to be effective against indicator bacteria in field trials. Studies to date have been limited on performance evidence for viruses in particular. However, in epidemiological studies, Almeida *et al.* (2001) found a potential negative association between Hepatitis A incidence and the presence of a household ceramic water filter in a study from urban poor section of Rio de Janiero, Brazil.

Therefore, it may be possible that some reduction of viruses is achievable with currently available point-of-use (POU) ceramic filters, although more testing is needed.

The proper use of drinking water treatment technology is as critical to its effectiveness as the technology itself (Draffin 1939). Limited presence/absence data on field microbiological effectiveness (24 pre- and post-treatment samples) reported by Lantagne (2001b) indicated that field effectiveness against total coliforms, H_2S-producing bacteria, and *E. coli* was substantially less than in lab studies summarized earlier (Lantagne 2001a). A lower observed effectiveness under field use conditions has been reported elsewhere (Baumgartner 2006; Roberts 2004). Lower reductions in the field suggest links between environmental factors or user behavior and technology effectiveness. In limited initial studies, however, Campbell (2005) and Lantagne (2001b) showed that filters can maintain effectiveness in field use for a long time (≥5 years). Hence, proper use can potentially ensure sustained access to microbiologically improved drinking water.

Microbe	n[a]	V[b]	Untreated[c]	Filtrate[d]	LRV[e]	Water[f]	Filter[g]	Reference
E. coli K12	6	36	6.9	1.9	5.0	Canal water[h]	CWP (Cambodia)	Van Halem (2006)
	6	36	6.9	0.48	6.4	Canal water	C.T. Filtron (Ghana)	Van Halem (2006)
	6	36	6.9	0	6.8	Canal water	Filtrón (Nicaragua)	Van Halem (2006)
	6	36	6.9	3.9	3.0	Canal water	Filtrón (Nicaragua), no Ag	Van Halem (2006)
Sulfite reducing clostridia	12	72	4.8	1.0	3.8	Canal water	CWP (Cambodia)	Van Halem (2006)
	12	72	4.8	0.95	3.8	Canal water	C.T. Filtron (Ghana)	Van Halem (2006)
	12	72	4.8	0	4.9	Canal water	Filtrón (Nicaragua)	Van Halem (2006)
	12	72	4.8	1.5	3.3	Canal water	Filtrón (Nicaragua), no Ag	Van Halem (2006)
MS2	2	<10?	3.7	3.4	0.3	?	Filtrón (Nicaragua)	Lantagne (2001a)
	6	<10?	5.6	4.7	0.9	?	CWP (Cambodia)	Van Halem (2006)
	6	36	5.6	4.7	0.9	Canal water	CWP (Cambodia)	Van Halem (2006)
	6	36	5.6	4.9	0.7	Canal water	C.T. Filtron (Ghana)	Van Halem (2006)
	6	36	5.6	5.1	0.6	Canal water	Filtrón (Nicaragua)	Van Halem (2006)
	6	36	5.6	4.4	1.2	Canal water	Filtrón (Nicaragua), no Ag	Van Halem (2006)
C. parvum	1	7	5.5	1.2	4.3	Reagent[i] grade	Filtrón (Nicaragua)	Lantagne (2001a)
G. intestinalis	1	7	5.4	0.85	4.6	Reagent grade	Filtrón (Nicaragua)	Lantagne (2001a)

a. Number of sample sets
b. Total spiked throughput (l) sampled
c. Concentration (arithmetic mean) per 100 ml sample, $\log_{10}$ units
d. Concentration (arithmetic mean) per 100 ml sample, $\log_{10}$ units
e. Arithmetic mean log reduction value (LRV) = $\log_{10}$ (untreated / filtrate).
f. Challenge water (water to which microbes were spiked)
g. Filter and location of manufacture; all are treated with some type of silver solution except where indicated.
h. Spiked canal water from the Netherlands.
i. Disinfected, dechlorinated water.

Table 3.1. Lab-based effectiveness testing for low-cost ceramic pot-style filters: summary of evidence to date.

3.2 Purpose and objectives

The purpose of this study was to evaluate the performance of three candidate porous ceramic water filters against bacterial and viral pathogen surrogates. The ceramic water purifier as produced by the NGO Resource Development International in Cambodia (the CWP1) was compared to a version of the filter modified with FeOOH (the CWP2) and a version without treatment by $AgNO_3$ (the CWP3). Both the CWP1 and CWP2 were treated with an aqueous solution of $AgNO_3$.

The specific objectives of this study were to:

- examine the effectiveness of the three filters against *E. coli* in the laboratory and in the field under a range of conditions;
- compare performance data from laboratory experiments with microbiological effectiveness data from filters in use in the field;
- compare the effectiveness of the filters against *E. coli* to currently used methods for water treatment (boiling) in the field;
- examine the effectiveness of the three filters against MS2, a viral surrogate, in the laboratory;
- collect enough data to reflect the variability of performance of the filters over extended use periods, and if possible, to identify associations between performance and factors like water characteristics;
- and evaluate the effects, if any, of $AgNO_3$ and FeOOH amendments to the performance of the CWP technology.

3.3 Methods and materials

Microbiological effectiveness testing of candidate filters proceeded in two parts, which are outlined in the following sections:

(i). Laboratory testing. Three different CWP type filters were subjected to extended laboratory testing in Cambodia for the reduction of bacterial and viral pathogen surrogates (*E. coli* and MS2) in spiked rain water and surface water.

(ii). Field testing. Two different CWP type filters were selected for field testing in household use over time (18 weeks) in a rural/peri-urban village. Reduction of the bacterial indicator *E. coli* was the key microbiological performance outcome measured.

3.3.1 Laboratory testing

Laboratory testing of three candidate low-cost, pot-style ceramic drinking water filters in Kandal province, Cambodia, was performed. Methods for laboratory testing of filters were intended to approximate use conditions in households in Cambodia. Challenge waters were rain water and surface waters that were in use as drinking water sources in the village of Prek Thom, Kandal province. Waters were collected and spiked with bacterial and viral pathogen surrogates, *E. coli* CN13 and bacteriophage MS2, respectively. Filters were tested over a greater than 600 l throughput to address variability in performance under challenge conditions. Filters were cleaned once per week during testing according to the manufacturers instructions.

3.3.1.1 Filters

The ceramic water purifier manufactured by RDI (CWP1) is a porous ceramic pot-style filter based on the ICAITI model promoted by Potters for Peace. The filters have been made in Kandal Province at a central factory since 2002. Raw clay is milled and mixed with ground rice husks, press molded, and fired to cone 012 (~870^{o}C) in a kiln using scrap wood pieces as fuel. After flow testing (a QA/QC step) to ensure that the flow rate is in the proper range to indicate target pore size and structure (1-3 l/hr), the porous filters are painted with a 0.00215 molar reagent-grade (99.999%) $AgNO_3$ solution intended to inhibit microbial growth on the filter. Approximately 300 ml are applied to each filter: 200 ml on the inside (46 mg Ag) and 100 ml on the outside of the filter element (23 mg Ag).

The CWP2 is a modified version of the RDI (CWP1) filter that contains a higher percentage of iron oxide-rich clay, based on prototype testing suggesting greater effectiveness of these filters against small, non-enveloped viruses (geometric mean virus reduction >4 $\log_{10}$ or 99.99%) in initial testing on limited volumes of spiked challenge waters (data not shown). Other details of manufacture are identical to the standard filter. The CWP2 is also painted with a silver nitrate ($AgNO_3$) solution.

The CWP3 is a variation of the RDI filter that does not employ silver or iron oxide amendments, but is the same in other respects. These filters are essentially the CWP1 without the application of silver nitrate.

3.3.1.2 Choice of test microbes

The non-pathogenic test microbes, *E. coli* CN13 (ATCC 700609) and bacteriophage MS2 (ATCC 15597-B1), were used as surrogates for bacterial and viral pathogens potentially present in drinking water sources, respectively. *Escherichia coli* is a gram negative, rod-shaped bacterium originating in the gut of warm blooded animals; cells are elongated, 1–2 µm in length and 0.1–0.5 µm in diameter. The well-characterized, non-pathogenic strain used was chosen due to its relative ease of production in the laboratory and its resistance to the antibiotic nalidixic acid, used to select for the bacterium in culture while excluding most other bacteria that might be present as interfering contaminants. Its size and morphology is characteristic of other pathogenic bacteria of concern in drinking water, such as pathogenic strains of *E. coli*, *Salmonella* spp., *Shigella* spp., *Campylobacter* spp. and *Vibrio* spp.. Hence, *E. coli* CN13 was chosen as a model for the reduction of bacterial pathogens in water through the primarily physical separation process of ceramic filtration. *E. coli* CN13 is also not infected by MS2 bacteriophage, making it suitable for concurrent use in filter testing with that virus as a test microbe in the same challenge water.

Bacteriophages like MS2 are useful surrogates for modeling the behavior of enteric viruses in water treatment processes (Grabow 2001) and have been used to model virus retention in other filtration processes (e.g., van Voorthuizen *et al.* 2001; Sobsey *et al.* , 1995a). MS2, a male-specific (F+), single stranded non-enveloped coliphage, is an appropriate surrogate for human enteric viruses, due to its similarity to poliovirus and hepatitis A virus in size (diameter = 24-25 nm), shape (icosahedral), and nucleic acid (RNA) (EPA 2003, 5-21; Dowd *et al.* 1998; Hassanizadeh and Schijven 2000). It is also useful in laboratory applications due to its ease of production, recovery, and enumeration; its nonpathogenic nature; and the ease of attaining high titers (Abbaszadegan *et al.* 1997). MS2 and other F+RNA viruses have been shown to be conservative estimators of sorption mechanisms when compared with mammalian viruses (Meschke 2001; Sobsey *et al.* 1995a; Bradford *et al.* 1993). Thus, it has been shown to be a conservative estimator of virus reduction performance in a wide range of treatment processes, including slow sand filtration (Schijven *et al.* 2003; Schijven *et al.* 2002; Schijven *et al.* 1999; Kinoshita *et al.* 1993; Powelson *et al.* 1990); bench scale modeling of drinking water treatment processes such as flocculation, coagulation, and sedimentation; rapid sand filtration; chlorine disinfection (Sobsey *et al.* 1995b); and UV disinfection (Tree *et al.* 2005; Jevons 1982; Wolfe 1990; Wilson 1992).

3.3.1.3 Overview of laboratory challenge testing

Filters were challenged with test waters A and B (Table 3.2), as representative of drinking water sources in Cambodia. Challenge water A was a relatively high quality water, with low turbidity and organic matter and low levels of *E. coli*. Challenge water B was of moderate quality, with a mean turbidity of 8.4, organic matter content as UV absorbance at 254 nm of 0.05, and a mean *E. coli* concentration of 145 colony forming units (cfu) per 100 ml. Each testing day water was collected from a rain water catchment system and a surface water used for irrigation and household use. Each water was spiked with either *E. coli* CN13 or MS2 or both and mixed for one minute. Then each filter was filled to the rim with spiked challenge water, approximately 10 l. Four to five hours later, filtrate (approximately 8 l) from each filter was collected, mixed manually with a sterile stirrer, and samples were taken of the post-treatment water for assay. Flow rates were approximately 2 l per hour when filters were full (10 l), decreasing with declining head. Total filter throughput per sampling day was approximately 10 l. Pre-treatment (spiked) water was placed alongside the filter unit in a separate closed container for the duration of the test, with both pre- and post-treatment water samples taken for analysis at time = 4 - 5 hr. Filter receptacles were completely drained but not disinfected between sampling days. Filters were cleaned once per week using methods recommended by RDI. During cleaning the filter and receptacle were scrubbed lightly with a brush, washed using boiled water, and reassembled for use. Methods for testing the filter in the laboratory were intended to replicate household use conditions. An exception to this would be the volume filtered per day, which in household use would usually be more than 10 l (up to 30 l).

Parameter	*Challenge water A: stored rain water[a] (mean, range)*	*Challenge water B: surface water[b] (mean, range)*
pH	7.0 (6.8 – 7.5)	7.8 (7.0 – 8.3)
Turbidity (NTU)	1.1 (<0.05 – 8.1)	8.4 (0.63 – 21)
E. coli / 100 ml before spike	<1 (<1 – 9.8)	145 (<1 – 540)
Temperature (^{o}C)	29 (22 – 34)	30 (24 – 34)
UV absorbance at 254 nm	0.01 (<0.001 – 0.03)	0.05 (0.01 – 0.08)

a. 12.3% of total households and 13.6% of rural households use rain water as a primary drinking water source, according to national data (NIS 2004).
b. 18.6% of total households and 21% of rural households use surface water as a primary drinking water source, according to national data (NIS 2004). Most of the remainder use dug wells as a source of drinking water. Access to well water is highly variable, however, and increasingly suspect as a source of drinking water in some areas due to arsenic contamination (Feldman *et al.* 2007).

Table 3.2. Laboratory challenge water characteristics.

3.3.1.4 Microbiological methods:

3.3.1.4.1 Production method for bacterial stocks

Escherichia coli CN13 (ATCC 700609) was used as the test microbe in laboratory bacterial challenge tests of filters. Bacteria were inoculated in tryptic soy broth (TSB) medium (Difco™) and incubated overnight (16 hours) at 37°C. The TSB medium was 3 g tryptic soy broth per 100 ml reagent water, sterilized, and allowed to cool to 30° C. Because *E. coli* CN13 is resistant to the antibiotic nalidixic acid, TSB for growing stocks was supplemented with 1% nalidixic acid (1g of nalidixic acid sodium salt dissolved in 100 ml reagent water, filter sterilized via a 0.22 μm pore size membrane filter assembly) at 0.1 ml nalidixic acid to 10 ml TSB (final concentration 100 mg/l) (USEPA 2001). After overnight incubation, 1 ml of *E. coli* culture was transferred aseptically to 30 ml of fresh TSB medium (with nalidixic acid) in a shaker flask and incubated at 37°C for 3-4 hours at 37°C, until absorbance was measured to be approximately 1.5 at 520 nm and cells were considered to be in stationary phase. Once cultures had reached the stationary growth phase, 20 ml samples were taken and centrifuged at 4800 x g for 20 minutes. The supernatant was discarded and the pellet of *E. coli* cells was washed 3 times and re-suspended in 20 ml of deionized (DI) water. One (1) ml of this mixture was added per 10 l of each challenge water (CW1 and CW2). The final concentration of *E. coli* CN13 was $10^4 – 10^7$ cfu/ml in challenge waters.

Laboratory bacteriophage challenge tests of filters were performed using the male-specific coliphage MS2 (ATCC 15597-B1). Stocks of high titer bacteriophage were spiked into each challenge water to influent concentrations of 10^5 - 10^8 pfu/ml. Both the influent and effluent were assayed for phages using the double agar layer (DAL) method as originally described by Adams (1959) and more recently standardized by the USEPA (2001).

3.3.1.4.2 Production method for virus stocks

Somatic and male-specific bacteriophages MS2 and φX-174 were propagated to obtain high-titer stocks for use in sorption experiments. Bacteriophages originally obtained from laboratory stocks were twice purified on *E. coli* C3000. Plaques were selected ("picked") from the bacterial lawn and suspended in phosphate-buffered saline (PBS). High titer stocks were produced through confluent lysis on soft agar with PBS-suspended phages, log-phase host (*E. coli* F-amp) and appropriate antibiotics and incubated at 37^{o}C for 24 hours. The lysate-agar mixture was subjected to chloroform extraction. Chloroform was added to the mixture in a 1:1 volume:volume ratio in 50 ml polypropylene centrifuge tubes, shaken vigorously by hand for three minutes, and centrifuged for 20 minutes at 4^{o}C at 2500 rcf. Following centrifugation, the supernatant was removed from individual centrifuge tubes and pooled. Sterile glycerol was added to the supernatant in a 1:4 volume:volume ratio. Finally, the stocks were aliquoted in 1ml polypropylene microcentrifuge tubes and stored at -80^{o}C. Phage stocks were assayed to determine titer using plaque assay techniques as described by Adams (1959) and more recently standardized by the EPA (USEPA 2001).

3.3.1.4.3 Microbiological analysis: *E. coli*

E. coli in samples was enumerated by filtering undiluted and diluted samples through 47-mm diameter, 0.45 μm pore size cellulose ester filters in standard, sterile magnetic membrane filter funnels and membranes were incubated on agar or broth media-soaked absorbent pads. Agar and broth media (Rapid HiColiform media, HiMedia, M1465/M1453), detected total coliform (TC) bacteria and *E. coli* by cleavage of a chromogenic β-galactoside substrate to detect total coliforms and a fluorogenic β –glucuronide substrate to detect *E. coli*, producing distinctive color TC colonies and blue fluorescing *E. coli* colonies under long-wave UV light at 366nm (Manafi and Kneifel 1989; Manafi *et al.* 1991; Geissler *et al.* 2000). Plates were incubated for 20 – 24 hours at 37^{o}C. These methods conform to EPA Approved Method 1604 (US EPA 2002), except HiMedia M1465 and 1453 were substituted for the more costly MI medium used in the EPA method. In preliminary studies in which samples were plated on both media, MI and M1465 or M1453, *E. coli* detection was comparable (data not shown). *E. coli* concentrations were expressed as colony forming units (cfu) per unit volume of water.

3.3.1.4.4 Microbial analysis: MS2 coliphages

MS2 bacteriophages were enumerated on tryptic soy agars containing appropriate antibiotics (streptomycin/ampicillin) using the double agar layer or spot titer pour plate plaque techniques (Adams 1959; Grabow and Coubrough 1986; USEPA 2001), with host *E. coli* F-amp (ATCC 700891; Debartolomeis and Cabelli 1991). Plaques were counted and bacteriophage concentrations are expressed as plaque forming units per unit volume of water. The two methods were not significantly different in preliminary comparison tests (data not shown), although the spot titer method does not have as low a detection limit as the DAL method due to the small volumes assayed (Meschke 2001). These methods are briefly described here.

The double agar layer (DAL) method

The double agar layer method was performed as described in EPA method 1602 (USEPA 2001). Samples were serially diluted in phosphate-buffered saline (PBS). Bottom agar was prepared as 1.4 – 1.5g Bacto-agar and 3g of tryptic soy broth per 100 ml of sterile, reagent-grade water, autoclaved, cooled to 42^{o}C, supplemented with streptomycin/ampicillin prepared according to method 1602, and poured into sterile, disposable 60mm x 15mm polystyrene or autoclaved glass Petri dishes.

Top agar was prepared as 0.7 – 0.8g Bacto-agar and 3g of tryptic soy broth per 100 ml of sterile, reagent-grade water, autoclaved, cooled to 42^{o}C, and supplemented with appropriate antibiotics. A series of 13 mm x 100mm sterile glass test tubes were filled with 7 ml of top agar while maintaining constant temperature at 42^{o}C in a water bath. To each tube was added 0.1 ml of log-phase host bacteria and 0.1 ml of sample (serial dilutions, vortexed). The contents of each tube (host, sample, and top agar) were poured onto bottom agar 60mm x 15mm polystyrene or glass plates. Top agar was allowed to solidify at room temperature. All plates were then inverted and incubated at 37^{o}C for 16-24 hours. Two or more dilutions and replicates were used, along with positive and negative controls.

Bacteriophages were enumerated on plates by counting clear zones of lysis (plaques) on the bacterial lawn and reported as plaque forming units per 100 ml sample (pfu/100 ml). Bacteriophages were enumerated from plates with most appropriate dilutions (those with 20-300 plaques).

The spot titer method

The spot titer method is similar to bacterial spot-plating using a single agar layer containing host bacteria and is derived from EPA method 1602 (USEPA 2001). Tryptic soy agar (TSA) was prepared as 0.7 – 0.8g Bacto-agar and 3g of tryptic soy broth per 100 ml of sterile, reagent-grade water, autoclaved, and cooled to 42^{o}C. Log-phase phage-specific *E. coli* host and appropriate antibiotics were added to nutrient agar at the ratio of 2ml log-phase host to 50ml agar. Log-phase host were prepared according to EPA method 1602 (USEPA 2001). Agar aliquots and log-phase *E. coli* host were poured into sterile, disposable 150mm x 15mm polystyrene or autoclaved glass Petri dishes and allowed to solidify. Five to ten replicates of 10 µl volumes of sample dilutions (diluted in PBS, vortexed) were spotted onto the agar/host mixture in a grid pattern. After drying plates in the biosafety hood, plates were inverted and incubated for 16-24h at 37^{o}C. Plaques were enumerated by counting clear zones of lysis (plaques) within the bacterial lawn and reported as plaque forming units per 100 ml sample (pfu/100 ml).

3.3.1.5 Analytical methodology

Filter influent and effluent were assayed for indicator bacteria and bacteriophages by methods 1604 and by methods 1602, respectively (USEPA 2002, 2001) as described. Reduction efficiency of microbes by filters was calculated and reported in $\log_{10}$ units according to:

Log_{10} reduction value (LRV) = $\log_{10}$ (pre-treatment concentration) – $\log_{10}$ (post-treatment concentration)

Log_{10} reductions of MS2 and *E. coli* from water by filtration were plotted against volume filtered. Histograms were plotted to examine the distribution of effectiveness as measured by reductions in test microbes.

3.3.2 Field testing

Water treatment technology performance under laboratory conditions may not represent performance in household use. In order to determine effectiveness of filters under field use conditions, filters were placed in households in Kandal Province, Cambodia. Sixty households received the CWP1 filter and 60 households received the CWP2. An additional 60 "control" households were also included in the intervention trial. Biweekly samples of raw, stored water and filter-treated or boiled water were taken for analysis.

3.3.2.1 Study site of Prek Thmey, Cambodia

The study site was the rural/peri-urban village of Prek Thmey, approximately 15 km from Phnom Penh, Cambodia in Kandal Province. Households receiving filters were trained in proper use and care of the filter by the project team, using materials and methods developed by Resource Development International (RDI), a local NGO that has performed several village-scale implementations of the technology in the region, most often with accompanying interventions for sanitation and hygiene within child and adult educational and vocational programs.

The 60 additional households served as controls for the duration of the project and followed their normal household water use and handling practices. Control households who practiced boiling of household drinking water also contributed samples to this study for a comparison of CWP1/CWP2 effectiveness versus boiling.

3.3.2.2 Filters

The CWP1 and CWP2 filter, described previously, were chosen for field evaluation for effectiveness against *E. coli*, a bacterial indicator of human fecal contamination of water. The CWP1 was the currently produced ceramic filter intervention in Cambodia, made at the RDI factory in Kandal Province. The CWP2 filter was made from iron oxide-rich base clay, which was associated with greater reductions of viruses in initial testing (data not shown). Filters were in all other respects identical. Filters were fired to cone 012, flow tested, and coated with $AgNO_3$. The two filters were indistinguishable in appearance.

3.3.2.3 Water sampling and sample handling

Microbiological effectiveness of filter units in household use was assessed through 9 bi-weekly visits at each household for sampling over 18 weeks. At each visit, a 250 ml sample of untreated, stored household water and a 250 ml sample of CWP1/CWP2 treated water were taken for analysis. When available, untreated and stored boiled water samples were taken from control households using that method of drinking water treatment. Samples were kept cold (on ice in a cooler) until delivery to the laboratory and thereafter stored at $4^{o}C$ until processing by membrane filtration, most often the same day and in all cases within 24 hours of the sampling event. Samples were collected from the household stored water by users who were asked to demonstrate their normal method of collecting water from the container for use that day. Samples of treated water were taken directly from the tap of the CWP1/CWP2 filter without flaming the tap or otherwise disinfecting it.

3.3.2.4 Water quality testing methods

E. coli in samples were enumerated in field samples by membrane filtration and incubation on selective media as described above in accordance with EPA Approved Method 1604 (USEPA 2002) with the substitution of HiMedia over MI culture media. Results were reported as colony forming units (cfu) per 100 ml sample. Nine rounds of water samples were taken from each study household over the 18 week sampling period (June-October 2006). Turbidity of water samples was measured in triplicate using a turbidimeter (Hach Pocket®) and the average values reported as NTU.

3.3.2.5 Data management and analysis

Water quality data were entered into a Microsoft Excel spreadsheet or Microsoft Access database and copied into Stata version 8.1 (Stata Corporation, College Station, TX, USA). All data were entered twice to ensure consistency and accuracy of data input.

E. coli concentrations in samples were calculated based on a minimum of two dilutions and three replicates according to Standard Methods (Clesceri *et al.* 1998). Filter effluent water quality data were stratified by source, turbidity, and raw water *E. coli* concentrations. Log_{10} reductions for *E. coli* were calculated for all complete sample sets (both pre- and post-treatment concentrations) for both filters tested overall and stratified by time in use (0 – 18 weeks).

3.3.3 Statistical analysis

Descriptive statistics were used to characterize the water quality testing results from laboratory and field samples, including arithmetic mean (with 95% confidence intervals), standard deviation, and variance of $\log_{10}$ reduction of *E. coli* and MS2. Parametric statistical tests were used to compare results. Comparisons were made initially using a two-sample mean comparison (t) test. In comparing $\log_{10}$ reduction values across parameters of filter type, challenge water, and other characteristics, ANOVA was used. Assumptions made in comparing $\log_{10}$ reduction data in parametric statistical testing were that data were normally distributed and groups had equal variances. All tests were compared using a significance level of $\alpha = 0.05$. Statistical testing was performed in Stata version 8.1 (Stata Corporation, College Station, TX, USA).

3.4 Results

3.4.1 Laboratory results

Results of repeated laboratory testing of filters for *E. coli* and MS2 reductions from seeded waters over time are summarized in Table 3.3. Figures 3.1 (*E. coli*) and 3.2 (MS2) summarize these results graphically.

3.4.1.1 Results by filter type

The results for repeated challenges indicate some variability in performance among filters in reducing both test microbes from both test waters. Complete filter challenge data are shown in Figures 3.3 to 3.14. The CWP1 reduced *E. coli* by a mean 2.4 $\log_{10}$ units (99.6%) and MS2 by a mean 1.0 $\log_{10}$ units (90%) in challenge water A (rain water) and *E. coli* by a mean 2.3 $\log_{10}$ units (99.5%) and MS2 by a mean 1.7 $\log_{10}$ units (98%) in challenge water B (surface water). The CWP2 reduced *E. coli* by a mean 2.1 $\log_{10}$ units (99.2%) and MS2 by a mean 1.4 $\log_{10}$ units (96%) in challenge water A and *E. coli* by a mean 2.2 $\log_{10}$ units (99.4%) and MS2 by a mean 1.3 $\log_{10}$ units (95%) in challenge water B. The CWP3 reduced *E. coli* by a mean 1.7 $\log_{10}$ units (98.1%) and MS2 by a mean 1.3 $\log_{10}$ units (95%) in challenge water A and *E. coli* by a mean 2.3 $\log_{10}$ units (99.5%) and MS2 by a mean 2.0 $\log_{10}$ units (99%) in challenge water B.

An ANOVA comparison of differences between filters tested showed significant differences for the reduction of *E. coli* ($p = 0.0020$) but not for MS2 ($p = 0.48$) among the CWP1, CWP2, and CWP3. Two sample mean comparison (t) tests between filter types suggested greater reduction of *E. coli* in CWP1 over CWP2 ($p = 0.021$) and for CWP2 over CWP3 ($p = 0.013$).

3.4.1.2 Results by water type

E. coli and MS2 $\log_{10}$ reductions by water type are given in Table 3.1 and in Figures 3.1 and 3.2. The CWP1 reduced *E. coli* by a mean 2.3 $\log_{10}$ (95% CI 2.0 – 2.6) in rain water and a mean 2.4 $\log_{10}$ (95%CI 2.1 – 2.6) in surface water. The CWP1 reduced MS2 by a mean 1.0 $\log_{10}$ (95% CI 0.37 – 1.6) in rain water and a mean 1.7 $\log_{10}$ (95%CI 1.1 – 2.3) in surface water. The CWP2 reduced *E. coli* by a mean 2.1 $\log_{10}$ (95% CI 1.8 – 2.3) in rain water and a mean 2.2 $\log_{10}$ (95%CI 1.9 – 2.5) in surface water. The CWP2 reduced MS2 by a mean 1.4 $\log_{10}$ (95% CI 0.71 – 2.0) in rain water and a mean 1.3 $\log_{10}$ (95%CI 0.82 – 1.8) in surface water. The CWP3 reduced *E. coli* by a mean 1.7 $\log_{10}$ (95% CI 1.5 – 2.0) in rain water and a mean 2.3 $\log_{10}$ (95%CI 2.2 – 2.5) in surface water. The CWP3 reduced MS2 by a mean 1.3 $\log_{10}$ (95% CI 0.83 – 1.7) in rain water and a mean 2.0 $\log_{10}$ (95%CI 1.7 – 2.3) in surface water.

ANOVA results indicate that *E. coli* reductions were different across all filters by challenge water ($p = 0.0009$) with challenge water B showing greater reductions. ANOVA results for MS2 reduction show a significant difference across filters by water type as well ($p = 0.0089$). Within filter types, two sample mean comparison (t) tests showed a significantly higher reduction of *E. coli* within CWP3 ($p < 0.0001$) but not for CWP1 ($p = 0.31$) or CWP2 ($p = 0.23$). For reduction of MS2 within water types, CWP1 ($p = 0.0005$) and CWP3 ($p = 0.0005$) showed significantly greater reduction using surface water; no significant difference was detected for CWP2 ($p = 0.60$).

3.4.1.3 Results by microbe type

ANOVA results for the difference in microbe type in performance data showed consistently higher reduction of *E. coli* than MS2 ($p < 0.0001$) across both challenge waters and filter types. These results are consistent with other studies by Van Halem (2006) and Lantagne (2001a).

3.4.1.4 Changes in microbial reduction over time

Log_{10} reductions of *E. coli* were not correlated with throughput over the limited volume tested; linear regression using volume filtered as the independent variable did not yield evidence of association ($R^2 = 0.016$) in data pooled from filter types and challenge waters. Similarly little evidence of correlation was observed between MS2 reduction and throughput over time ($R^2 = 0.17$).

Greater reductions of both MS2 and *E. coli* were observed in initial testing of filters (within the first 100 l) in both challenge waters and in all filter types. For *E. coli*, the mean log_{10} reduction was 2.9 log10 (95% CI 2.5 – 3.4) within the first 100 l of testing and 2.1 log_{10} (95% CI 2.0 – 2.2) thereafter ($p < 0.0001$). For MS2, the mean log_{10} reduction was 4.1 log10 (95% CI 3.5 – 4.8) within the first 100 l of testing and 1.2 log_{10} (95% CI 1.1 – 1.3) thereafter ($p < 0.0001$). The effect was consistent and significant in both challenge waters and in all filters tested for both *E. coli* and MS2.

3.4.2 Field results

3.4.2.1 Results by treatment type

Treatment by use of a CWP1, CWP2, or boiling resulted in significant reductions of *E. coli* in household stored water (Figures 3.15 and 3.16). Treatment by boiling (n = 282 paired samples of treated and untreated water) resulted in an arithmetic mean 1.9 log_{10} reduction in *E. coli* (95% CI 1.7 – 2.0). Treatment by use of the CWP1 (n = 485 paired samples of treated and untreated water) resulted in an arithmetic mean 2.1 log_{10} reduction in *E. coli* (95% CI 2.0 – 2.2). Treatment by use of the CWP2 (n = 496 paired samples of treated and untreated water) resulted in an arithmetic mean 2.0 log_{10} reduction in *E. coli* (95% CI 1.9 – 2.1). Effect of treatment type on *E. coli* log_{10} reduction as determined by ANOVA yielded a significant result ($p < 0.0001$) indicating significant differences between methods.

Two sample t tests (unpaired) indicated that the log_{10} reduction of *E. coli* by the CWP1 was greater than by boiling ($p = 0.0002$). Reduction of *E. coli* was not greater in the CWP2 than boiling ($p = 0.36$). The log_{10} reduction of *E. coli* by the CWP1 was significantly greater than by the CWP2 ($p = 0.0003$). Therefore the order of effectiveness against *E. coli* of the water treatments was observed to be CWP1 > boiling = CWP2.

The calculation of log_{10} reduction of *E. coli* in field samples was often limited by a non-detect in the treated water effluent (*E. coli*/100 ml < 1 cfu), resulting in a log_{10} reduction value (LRV) that was a function of the measured *E. coli* in the untreated water sample only. This was the case for 124 samples of water treatment by boiling (44% of all samples), 231 CWP1 samples (48%), and 222 CWP2 samples (45%). There was a substantial difference in the calculated log_{10} reduction of *E. coli* between samples that were limited by untreated water *E. coli* counts (<1 cfu/100 ml post-treatment) and those that included detectable *E. coli* in post-treatment water samples. For boiled water samples, the arithmetic mean $\log_{10}$ reduction of *E. coli* was 2.6 (95%CI 2.4 – 2.8) among samples with *E. coli* non-detects in post-treatment water, versus 1.4 $\log_{10}$ (95% CI 1.2 – 1.6) for those with detectable *E. coli* in post-treatment water, a difference of 1.2 $\log_{10}$ ($p < 0.0001$) was observed. Similarly, for water samples taken pre- and post-treatment for the CWP1 filter, sample sets including a post-treatment non-detect for *E. coli* resulted in a $\log_{10}$ reduction of 2.6 (95% CI 2.5 – 2.7), versus 1.6 $\log_{10}$ (95% CI 1.5 – 1.8) where detectable *E. coli* remained ($p < 0.0001$). In CWP2 samples, the difference was 2.4 $\log_{10}$ (95% CI 2.2 – 2.5) versus 1.7 $\log_{10}$ (1.6 – 1.8), also significant at the $\alpha = 0.05$ level ($p < 0.0001$).

The $\log_{10}$ reduction of *E. coli* in field samples varied considerably for all treatment methods, with reductions generally following a normal distribution about a mean of 2 $\log_{10}$, with some samples in the negative range and others above 4 $\log_{10}$. Plots of distributions of these data are presented in Figures 3.17 – 3.19.

The distribution of *E. coli* counts in 100 ml treated water samples are shown in figures 3.20 – 3.22. For the CWP1, arithmetic mean *E. coli* counts per 100 ml were 110 (95% CI 41-170) and geometric mean counts were 16 (95% CI 13-20) against arithmetic and geometric mean pre-treatment concentrations of 3800 (95% CI 2200-5400) and 510 (95% CI 420-630), respectively. For the CWP2, arithmetic mean *E. coli* counts per 100 ml were 110 (95% CI 57-170) and geometric mean counts were 14 (95% CI 11-18) against arithmetic and geometric mean pre-treatment concentrations of 2000 (95% CI 1300-2600) and 410 (95% CI 340-500), respectively. For boiling, arithmetic mean *E.*

coli counts per 100 ml were 120 (95% CI 68-170) and geometric mean counts were 24 (95% CI 17-33) against arithmetic and geometric mean pre-treatment concentrations of 2900 (95% CI 1570-4300) and 450 (95% CI 340-580), respectively.

3.4.2.2 Results by water type

An ANOVA for *E. coli* $\log_{10}$ reduction by stored household water source indicated a significantly greater reduction of indicator bacteria in surface water sources ($p < 0.0001$) such as river water. All households included in the study were within 500 m of the Bassac river, a primary drinking water source. Similar associations were not observed for rain water ($p = 0.77$) or well water sources ($p = 0.25$ for tube wells; $p = 0.46$ for hand-dug wells). Water source categories were not mutually exclusive; 13.8% (n = 273) of samples sets taken from household (untreated) stored water were from more than one source.

An additional ANOVA was used to examine the source-specific $\log_{10}$ reduction of *E. coli* stratified by method of water treatment. For households reporting boiling water, surface water was associated with higher levels of *E. coli* reduction ($p < 0.0001$), as was the use of a tube well ($p < 0.0001$). Reductions in rain water were not significantly greater ($p = 0.98$). Insufficient numbers of households in this grouping reported use of a hand-dug well, so p-values for this analysis were not computed for that source.

For samples taken from the CWP1, the use of surface water was not associated with a greater reduction of *E. coli* ($p = 0.91$) but the use of rain water was ($p = 0.031$). The use of water from a tube well ($p = 0.095$) or hand dug well ($p = 0.30$) was not associated with higher levels of *E. coli* reduction through use of a CWP1.

For samples taken from the CWP2, the use of surface water was associated with a greater reduction of *E. coli* ($p < 0.0001$) but the use of rain water was not ($p = 0.22$). The use of water from a tube well ($p = 0.38$) was not associated with higher levels of *E. coli* reduction through use of a CWP1. Insufficient numbers of households in this grouping reported use of a hand-dug well, so p-values for this analysis were not computed for that source.

3.4.2.3 Results by turbidity

The arithmetic mean turbidity in stored, boiled water samples was 9.1 NTU, versus 2.6 NTU for effluent samples taken from the CWP1 and 2.9 NTU in CWP2 samples. Untreated water turbidity (arithmetic mean = 8.9 NTU, 95% CI 8.6 NTU – 9.3 NTU) was not significantly different between sample sets from boiling or treatment by either filter according to ANOVA. Boiled water samples were significantly more turbid ($p < 0.0001$) than CWP1 or CWP2 effluent samples. Measured turbidity in filter effluent samples from the CWP1 and CWP2 were not significant at the 0.05 level.

ANOVA determination of the effect of turbidity levels in the untreated water on $\log_{10}$ reduction of *E. coli* yielded a significantly greater reduction at turbidity levels higher than 10 NTU for treatment by boiling ($p = 0.0057$), use of the CWP2 ($p = 0.0028$), and a result at the margin of significance for use of the CWP1 ($p = 0.057$). Linear regression using $\log_{10}$ reduction of *E. coli* as a dependent variable and untreated water turbidity as the continuous independent variable were not correlated with use of a CWP1 ($R^2 = 0.0012$), a CWP2 ($R^2 = 0.0048$) or boiling ($R^2 = 0.012$). Results indicate a weak correlation between $\log_{10}$ reduction of *E. coli* and turbidity but this association is not clear across turbidity levels, especially for turbidity < 10 NTU. In this study, 370 samples of untreated water (19% of all samples) had turbidity greater than 10 NTU.

3.4.2.4 Results by time

ANOVA determination of the effect of time in use on $\log_{10}$ reduction of *E. coli* over the follow up period (18 weeks) by treatment method yielded a significant result for water treatment by the CWP1 ($p < 0.0001$), use of the CWP2 ($p < 0.0001$), but not for boiling ($p = 0.11$). Plots of the $\log_{10}$ reduction over the study period (Figures 3.23 and 3.24) show wide variation in the performance of the CWP1 and CWP2 during the follow up. Because rainfall is known to be an important determinant of water quality and availability, linear regression was performed to determine whether any association existed between rainfall and *E. coli* reduction over time, with rainfall in mm (two week cumulative) as a continuous independent variable. No association was observed ($R^2 = 0.0036$).

3.4.3 Comparing laboratory and field results

Laboratory and field results agreed for log10 reduction of *E. coli* by use of the CWP1. Results for *E. coli* reduction in the laboratory pooled across rain water and surface waters (challenge waters A and B) yielded a mean of 2.3 $\log_{10}$ (95% CI 2.1 – 2.5, n = 68). The mean field $\log_{10}$ reduction was 2.1 (95% CI 2.0 – 2.2, n = 485). An unpaired t test assuming equal variances in the data yielded a p-value of 0.097.

CWP2 results in the laboratory and field also agreed for reduction of *E. coli*. Laboratory results (pooled across challenge waters A and B) indicate a 2.1 $\log_{10}$

reduction of *E. coli* (1.9 – 2.3, n = 68) versus a mean 2.0 $\log_{10}$ reduction (95% CI 1.9 – 2.1) in field use ($p = 0.32$).

3.5 Discussion

3.5.1 Laboratory results

3.5.1.1 Laboratory results by filter type

E. coli reduction by filters CWP1, CWP2, and CWP3 were all near 99% under challenge conditions, although the CWP1 did marginally outperform the other two. MS2 reductions for all three filters were comparable, with mean reductions of 90% - 99%. Results suggest little effect of $AgNO_3$ or FeOOH additives on the performance of the filters against these indicators. These numbers are lower than other reported values for reduction of *E. coli* and higher than reported reduction values for MS2 from other laboratory studies over limited volumes using similar filters and different challenge waters (Van Halem 2006; Lantagne 2001).

3.5.1.2 Laboratory results and changes over time

Filter challenge tests are frequently carried out using relatively low volumes of challenge water. Results reported here suggest that initial performance of filter in challenge testing in low volumes (e.g., under 100 l) may not be indicative of consistent levels of performance over time. Results from the first 100 l of challenge testing were significantly higher in all filter types, in both challenge waters, and for both microbes tested, in several cases more than one order of magnitude higher.

3.5.2 Field results

3.5.2.1 Field results by treatment type

Although the reduction of *E. coli* by the CWP1 was shown to be significantly greater than either boiling or use of the CWP2, the observed differences in effectiveness were small. And because these results indicate only a marginally greater performance for one treatment method against one bacterial indicator organism, these results do not strongly indicate that one of these methods is more effective overall for the treatment of household drinking water. The reduction of *E. coli* in household samples for all treatment methods followed a log-normal distribution centered around 99% reduction, with reduction as high as 99.9999% and also negative reductions.

Negative log reduction values occurred in 24 sample sets of CWP1 (4.9%), 25 of CWP2 (5.0%), and 23 sample sets of boiled water (8.2%) when comparing *E. coli* counts in untreated versus treated water, indicating higher levels in the treated water. The observation of increased levels of *E. coli* in treated water may be related to improper handling or water storage methods (in the case of boiled water), improper cleaning of the filters by users, changing levels of *E. coli* in water over time including the possibility of regrowth in the treated water (Desmarais *et al.* 2002) or die-off in the untreated water, or other factors. These results are consistent with several studies (e.g., Wright *et al.* 2004 and Jensen *et al.* 2002) showing that recontamination of stored water in the home could significantly impact the quality of potable water used in the household.

3.5.2.2 Field results by turbidity

The CWP1 and CWP2 filter effluent mean turbidities were significantly lower than the post-treatment turbidity of boiled water, as expected. No difference was observed in the turbidity of samples from the CWP1 and CWP2.

Greater reduction of *E. coli* was associated with increased turbidity for all treatment types. One possible reason for this is the slightly greater concentrations of *E. coli* observed in turbid water. For example, out of a total 1906 samples of untreated, stored household water with turbidity data, the arithmetic mean *E. coli* count (cfu/100 ml)was 2.5×10^3 (95% CI $1.8 \times 10^3 - 3.1 \times 10^3$) in samples (n = 1609) with turbidity ≤ 10.0 NTU and 4.6×10^3 (95% CI $2.1 \times 10^3 - 7.2 \times 10^3$) in samples (n = 297) with turbidity > 10.0 NTU, a statistically significant difference ($p < 0.0001$). The greater concentration of *E. coli* in relatively turbid water could be associated with water source characteristics, a clarification step performed by users (such as settling/storage, which may be linked to a reduction in microbes via die-off in storage), or microbial association with particulates in water. This association is not strong, however.

3.5.2.3 Field results by time in use

Filter effectiveness in the field was maintained over the 18 week trial period, with 120 households reporting daily use of approximately 20 l. Variability in the *E. coli* reductions by the CWP1 and CWP2 filters over the study period may be associated with variations in source water quality, changes in filter use, changes in filter performance, or other unmeasured factors.

3.5.3 Comparing laboratory and field testing results

Studies have reported lower effectiveness of filters in field use (Baumgartner 2006; Roberts 2004). In this study, field performance of the two CWP filters was nearly comparable to laboratory performance for *E. coli* reduction. The CWP1 reduced *E. coli* in stored household water by approximately 99% (arithmetic mean 2.1 $\log_{10}$, 95% CI 2.0 – 2.2 $\log_{10}$, n = 485 total sample sets). The CWP2 reduced *E. coli* by an approximately equivalent amount of nearly 99% (arithmetic mean 2.0 $\log_{10}$, 95% CI 1.9 – 2.1 $\log_{10}$, n = 496 total sample sets). The approximately 2 $\log_{10}$ reductions by CWP1 and CWP2 in the field are only somewhat lower than their reductions observed in the laboratory, with mean laboratory reductions of 2.3-2.4 $\log_{10}$ for CWP1 and 2.1-2.2 $\log_{10}$ for CWP2.

Evidence suggests that the calculated $\log_{10}$ reduction of *E. coli* in field samples by all treatment methods underestimates performance because non-detects in treated water samples limit the LRV. This amounts to computed LRV for these samples representing potential minima for reduction of *E. coli*. Results from the field were consistent with tests from the laboratory for $\log_{10}$ reduction of *E. coli*, however, so this interpretation may not be warranted. Even though a large percentage of samples sets in the field were limited by non-detects of *E. coli* in treated water (not the case in any laboratory samples), the LRV means from laboratory and field samples were not significantly different.

3.5.4 Standards of performance

Extensive laboratory and field testing of point-of-use water treatment technologies is needed to characterize their performance as water quality interventions. Because ceramic water purifiers (water treatment filters) are being promoted as means of improving water quality and lowering diarrheal disease, substantial levels of microbial reductions may be needed in field use to produce water that is of low risk.

In the United States and in other rich countries, microbiological effectiveness standards based on reductions of pathogenic or indicator microbes apply to point of use water treatment devices. The United States Environmental Protection Agency and the National Sanitation Foundation (now NSF-International) require that water treatment devices intended to produce potable drinking water consistently meet a six $\log_{10}$ reduction of bacteria, four $\log_{10}$ reduction of viruses, and a three $\log_{10}$ reduction of protozoa (USEPA 1987, NSF 2003), using key surrogate microbes over a range of challenge water quality characteristics. The filters tested in this study would not meet the required level of performance for bacteria or viruses. The risk-based approach for setting technology performance standards, however, now advocated by the World Health Organization (WHO 2006), recognizes the need for incremental improvement in water quality that can have real benefits where waterborne disease burdens are high. Because relatively modest improvements in water quality at the household level may result in substantial health gains in some settings, technologies not achieving the levels of microbial reduction required in rich countries should be studied further for potential health impacts in developing countries.

3.5.5 Previous studies

Data on the laboratory and field performance of the CWP-type filter are limited. Van Halem (2006) suggests that filters produced at the same factory (RDI, Kandal Province, Cambodia) can provide approximately 99.9% reduction in *E. coli*, with <90%

reduction of MS2. These values fall within the range of our testing data, although we found lower mean reductions in *E. coli* and higher mean reductions of MS2.

3.5.6 Relevance of these findings to other CWP programs

Low cost ceramic filtration for drinking water treatment in developing countries is diverse, varying by overall design, production method, clay and other materials, quality assurance and quality control (QA/QC) procedures, burnout material, firing temperatures and methods, chemical (e.g., colloidal silver) amendments, and other characteristics (Lantagne 2001; Sobsey 2002; Cheesman 2003; Dies 2003). Because the design and available materials and methods vary widely from region to region, effectiveness data for one ceramic filter design may not be representative of other systems, or even in some cases of separate batches of filters made at the same factory where production methods are not highly controlled. Moreover, pot-style ceramic filtration technologies are changing as NGOs and others work to test and improve the technologies to be more effective interventions for improving water quality at the point of use. Because the Filtrón (CWP) model has been widely replicated worldwide and adapted to local conditions, the effectiveness data presented here may or may not be generalizable. More work is clearly needed to increase the evidence base of effectiveness for these promising interventions.

3.5.7 Future work

Low-cost testing methods are now available to evaluate the microbiological effectiveness of water treatment technology in developing countries, and these should be used to evaluate technologies for use at the local level. Laboratory and field-based testing of interventions will be critical in building the evidence base for decentralized water treatment options. Because available resources, technologies, target contaminants, concentrations of microbes and other contaminants in drinking water sources, water quality characteristics, population susceptibility to waterborne infectious diseases, and other factors vary widely in the developing world, local-based intervention testing for specific intervention objectives is warranted, including microbiological testing. These data can then be used in a risk-based model (e.g., Howard *et al.* 2006) to evaluate the extent to which treatment is needed and the health effects of providing safe water given local water quality, quantity, and use conditions.

3.6 Conclusions

Key findings from this study are articulated below.

- The CWP1 and CWP2 significantly reduced surrogates for waterborne bacterial and viral pathogens, with a mean of approximately 99% (2 $\log_{10}$) reduction for *E. coli* bacteria (laboratory and field testing) and 90-99% (1 - 2 $\log_{10}$) reduction for viruses (laboratory testing only).
- Laboratory and field reduction of *E. coli* by filters were comparable.
- Reduction of *E. coli* was greater in the CWP1 filter, followed by the CWP2 and CWP3 filters in laboratory testing.
- The CWP1 reduced *E. coli* in field testing to a marginally greater extent than did the CWP2.

- The reduction of MS2 in laboratory testing was not significantly different between filters.
- The application of silver compounds to CWP-type filters is widely held to increase microbiological effectiveness but this was not observed in this study. The CWP3, having no application of silver, was observed to be comparable in microbiological effectiveness to the CWP1 and CWP2 (with silver amendment).
- The addition of iron oxide amendments to the base clay before firing (CWP2) did not significantly change the microbiological effectiveness of the filters in the laboratory or in the field against *E. coli* or MS2.
- Effectiveness of filters against the bacterial indicator *E. coli* was maintained during field use conditions over 18 weeks, although statistically significant changes in mean reductions over the sample period were observed.
- Log_{10} reductions of *E. coli* in boiled water samples were comparable to performance of the filters over the 18 week field trial. This finding suggests that boiled water may be recontaminated after treatment through improper storage.
- Reduction of microbes was marginally higher in more turbid waters, both in the laboratory and in the field, probably due to either particle association of microbes or higher levels of *E. coli* in field samples with higher turbidity.

Filter	*Microbe*	*Challenge water*	*n*[a]	*V*[b] *(l)*	*Mean influent (log_{10} units)*[c]	*Mean filtrate (log_{10} units)*[d]	*LRV mean*[e]	*95% CI*	*LRV std dev*	*LRV variance*
CWP1	*E. coli*	Rain water (A)	34	660	4.6	2.3	2.3	2.0-2.6	0.83	0.69
		Surface water (B)	34	660	5.1	2.7	2.4	2.1-2.6	0.72	0.51
	MS2	Rain water (A)	17	660	6.9	5.6	1.3	0.47-2.1	1.6	2.6
		Surface water (B)	17	660	6.6	4.9	1.7	1.1-2.3	1.2	1.4
CWP2	*E. coli*	Rain water (A)	34	660	4.6	2.6	2.1	1.8-2.3	0.77	0.59
		Surface water (B)	34	660	5.1	2.9	2.2	1.9-2.5	0.79	0.62
	MS2	Rain water (A)	17	660	6.9	5.4	1.4	0.73-2.0	1.3	1.6
		Surface water (B)	17	660	6.6	5.4	1.3	0.82-1.8	0.97	0.93
CWP3	*E. coli*	Rain water (A)	68	1340	4.6	2.9	1.8	1.5-2.0	1.0	1.0
		Surface water (B)	68	1340	5.1	2.7	2.4	2.2-2.6	0.73	0.53
	MS2	Rain water (A)	34	1340	6.9	5.6	1.3	0.83-1.7	1.2	1.6
		Surface water (B)	34	1340	6.6	4.8	1.9	1.7-2.2	0.78	0.62

a. Number of sample sets
b. Total spiked throughput (l)
c. Concentration (arithmetic mean) per 100 ml sample, log_{10} units
d. Concentration (arithmetic mean) per 100 ml sample, log_{10} units
e. Arithmetic mean log reduction value (LRV) = log_{10} (influent / filtrate).

Table 3.3. Summary of laboratory effectiveness data for the CWP1, CWP2, and CWP3 ceramic filters.

Treatment method	Water source[a]	n[b]	Mean influent (log_{10} units)[c]	Mean effluent (log_{10} units)[d]	LRV mean[e]	95% CI	LRV std dev	LRV variance
CWP1	All	485	3.6	1.5	2.1	2.0-2.2	1.2	1.4
	Rain water	368	3.5	1.4	2.1	2.0-2.2	1.2	1.4
	Surface water	102	3.4	1.4	2.1	1.9-2.3	1.3	1.6
	Well water	77	3.9	1.5	2.4	2.2-2.6	1.0	1.0
	Other/not known	0	-	-	-	-	-	-
CWP2	All	496	3.3	1.3	2.0	1.9-2.1	1.1	1.2
	Rain water	327	3.3	1.3	2.0	1.9-2.1	1.1	1.2
	Surface water	116	3.1	1.0	2.1	1.9-2.3	1.0	1.1
	Well water	109	3.3	1.3	2.0	1.8-2.2	1.1	1.2
	Other/not known	0	-	-	-	-	-	-
Boiling	All	282	3.5	1.5	1.9	1.7-2.0	1.3	1.7
	Rain water	137	3.5	1.6	1.9	1.6-2.1	1.3	1.6
	Surface water	64	3.3	1.1	2.2	2.0-2.5	1.2	1.4
	Well water	74	3.3	1.8	1.5	1.2-1.8	1.3	1.8
	Other/not known	59	3.5	1.5	2.0	1.7-2.4	1.3	1.7

a. Sources are not mutually exclusive. Samples were taken from the household stored water, which could have come from multiple sources.
b. Number of matched raw/treated water samples.
c. Concentration (arithmetic mean) per 100 ml sample, log_{10} units
d. Concentration (arithmetic mean) per 100 ml sample, log_{10} units
e. Arithmetic mean log reduction value (LRV) = log_{10} (pre-treatment concentration / filtrate concentration).

Table 3.4. Field effectiveness data summary for water treatment by boiling, the CWP1, and the CWP2 over the 18 week trial.

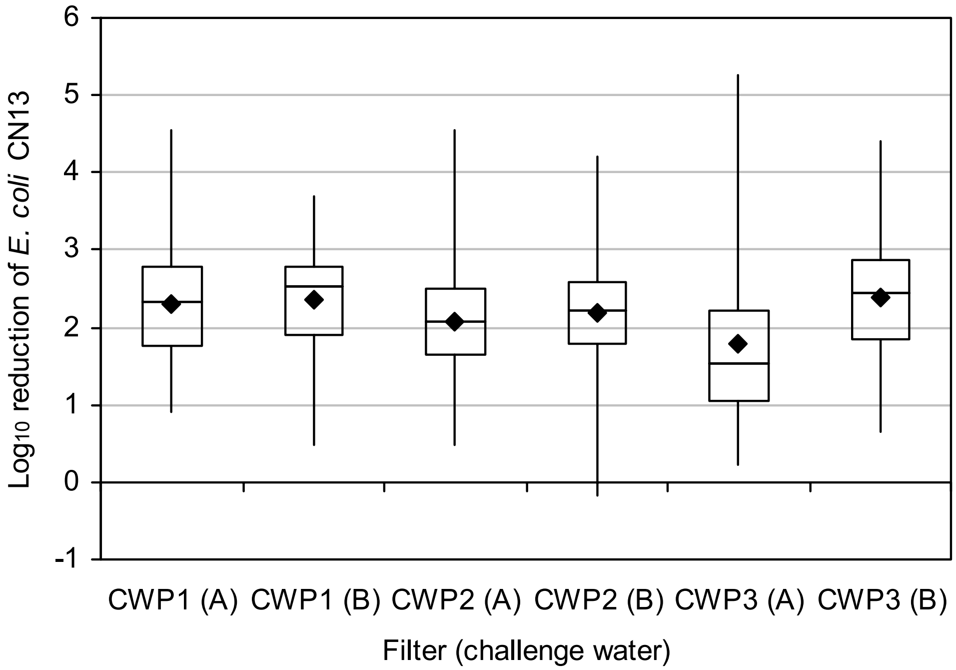

Figure 3.1. Box-and-whisker plot for $\log_{10}$ reduction of *E. coli* CN13 by filter type (CWP1, CWP2, CWP3) and challenge water (A, B). Upper and lower points represent maxima and minima, boxes indicate 25^{th} and 75^{th} percentile boundaries, the line break within each box represents the median value, and the points are arithmetic means for all sample sets.

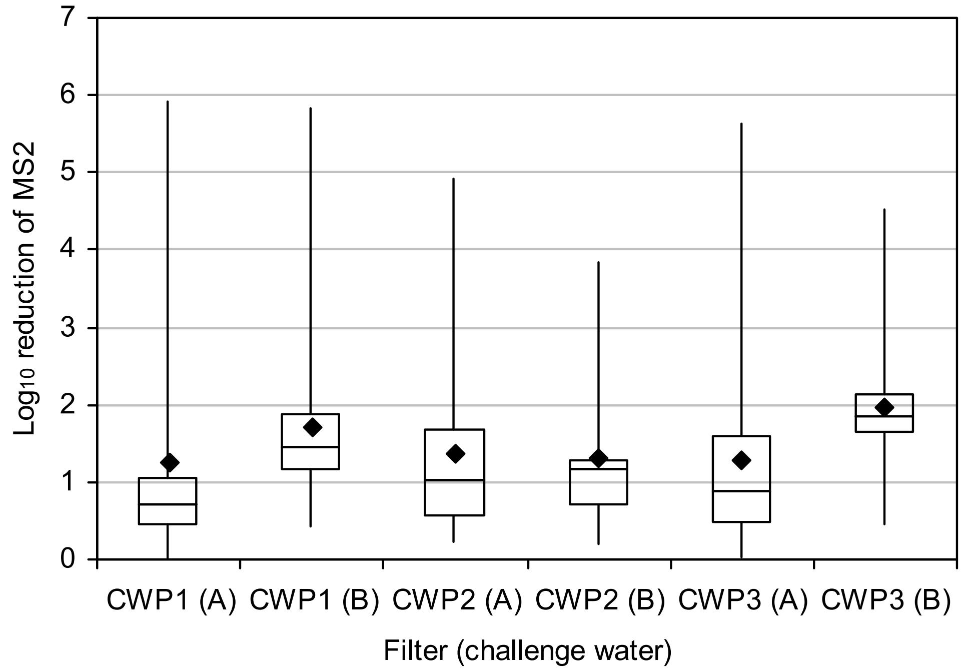

Figure 3.2. Box-and-whisker plot for $\log_{10}$ reduction of MS2 by filter type (CWP1, CWP2, CWP3) and challenge water (A,B). Upper and lower points represent maxima and minima, boxes indicate 25^{th} and 75^{th} percentile boundaries, the line break within each box represents the median value, and the points are arithmetic means.

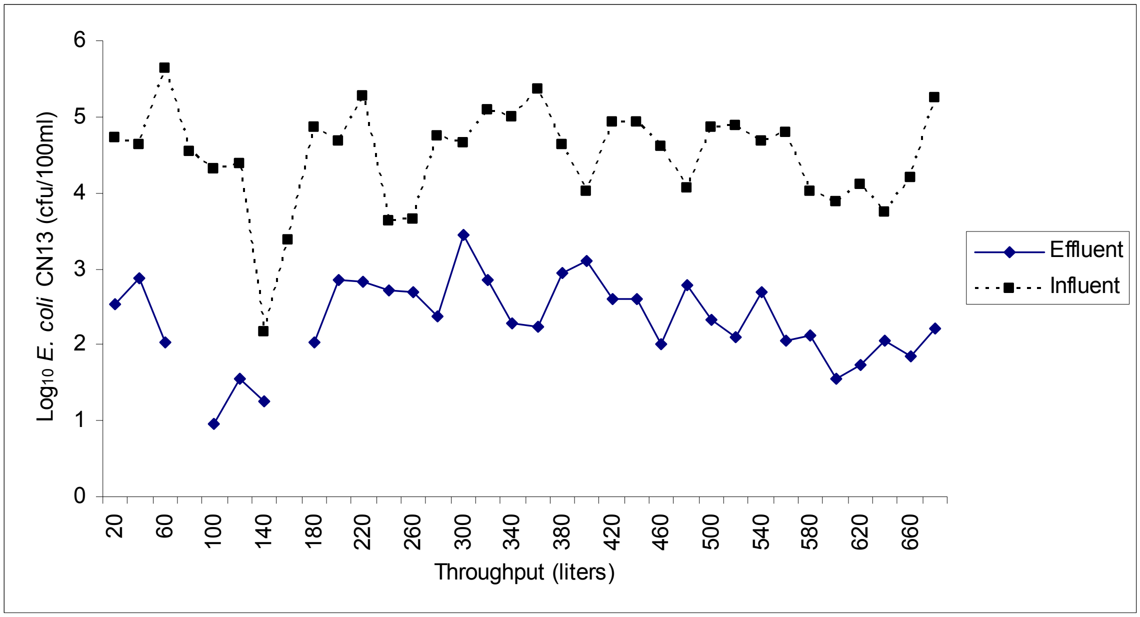

Figure 3.3. Log_{10} concentrations of *E. coli* CN13 in CWP1 against spiked rain water (challenge water A) over 680 l (n = 34 sampling events) in both influent and effluent.

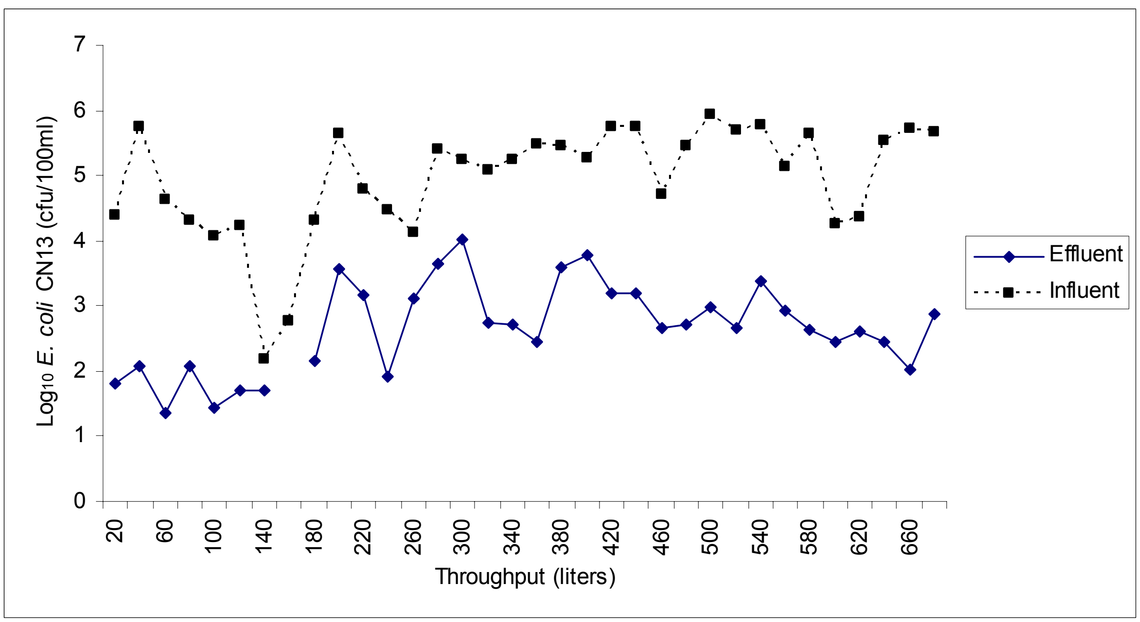

Figure 3.4. Log_{10} concentrations of *E. coli* CN13 in CWP1 against spiked surface water (challenge water B) over 680 l (n = 34 sampling events) in both influent and effluent.

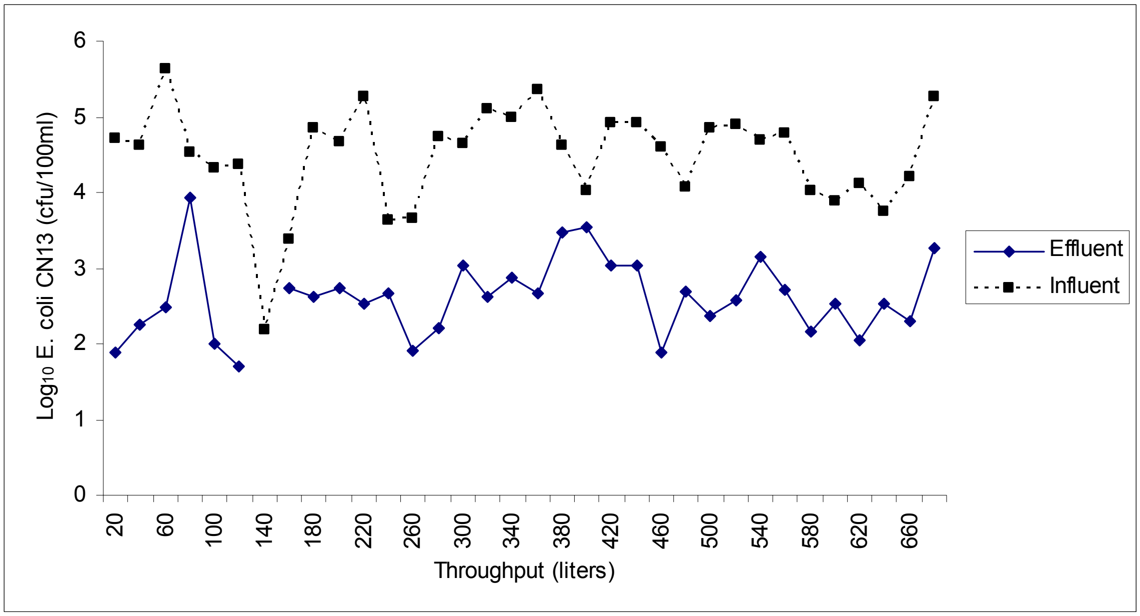

Figure 3.5. Log_{10} concentrations of *E. coli* CN13 in CWP2 against spiked rain water (challenge water A) over 680 l (n = 34 sampling events) in both influent and effluent.

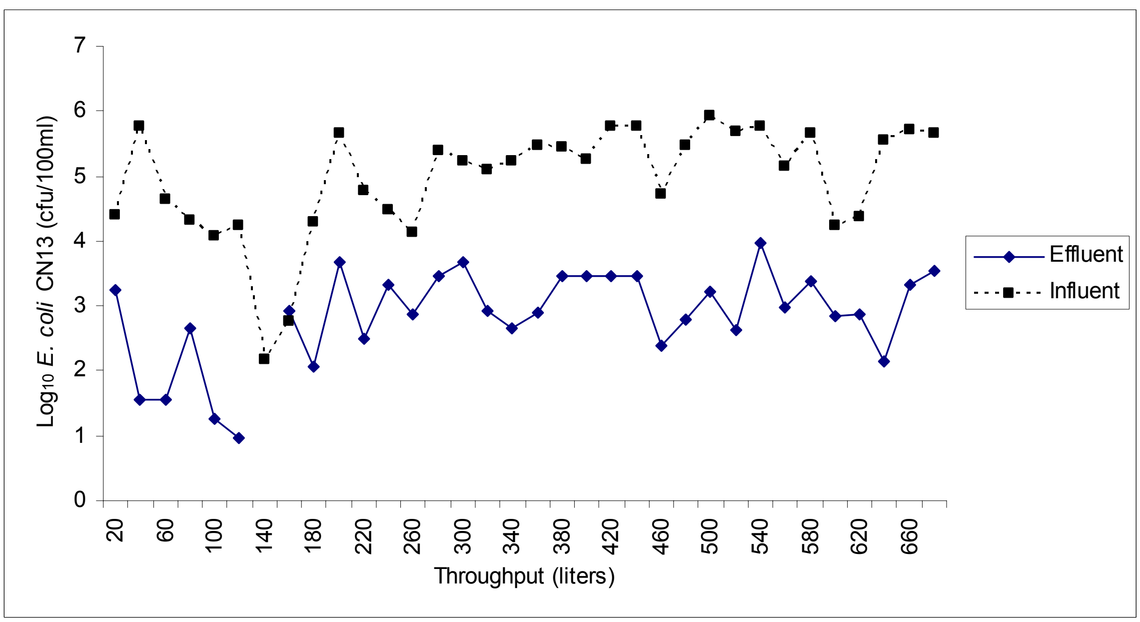

Figure 3.6. Log_{10} concentrations of *E. coli* CN13 in CWP2 against spiked surface water (challenge water B) over 680 l (n = 34 sampling events) in both influent and effluent.

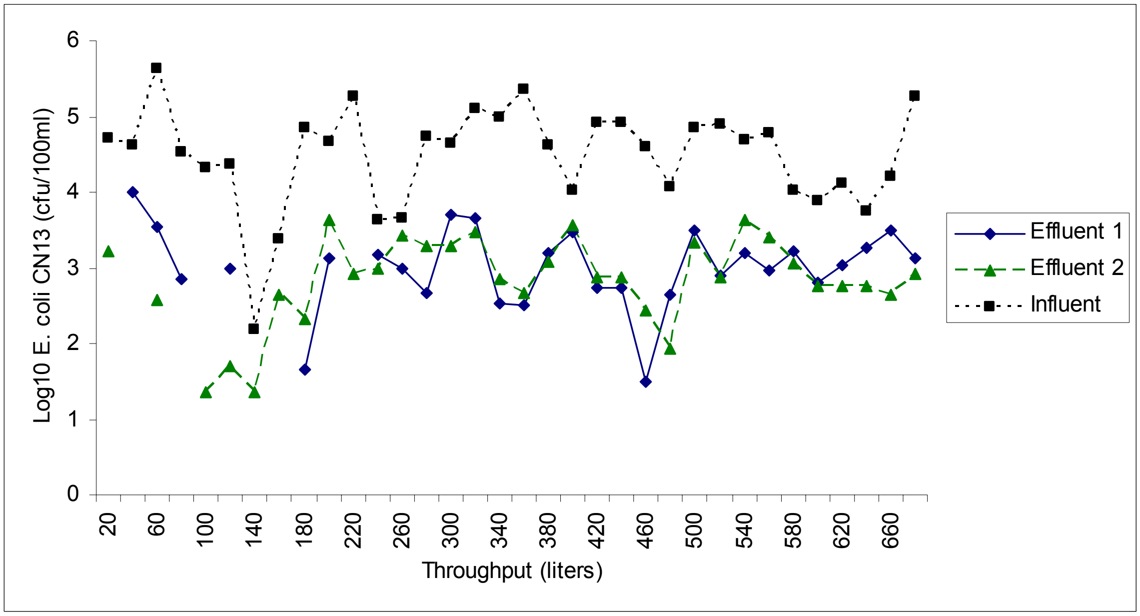

Figure 3.7. Log_{10} concentrations of *E. coli* CN13 in CWP3 (two units run in parallel) against spiked rain water (challenge water A) over 680 l each (total volume 1360 l) (n = 34 sampling events per unit) in both influent and effluent.

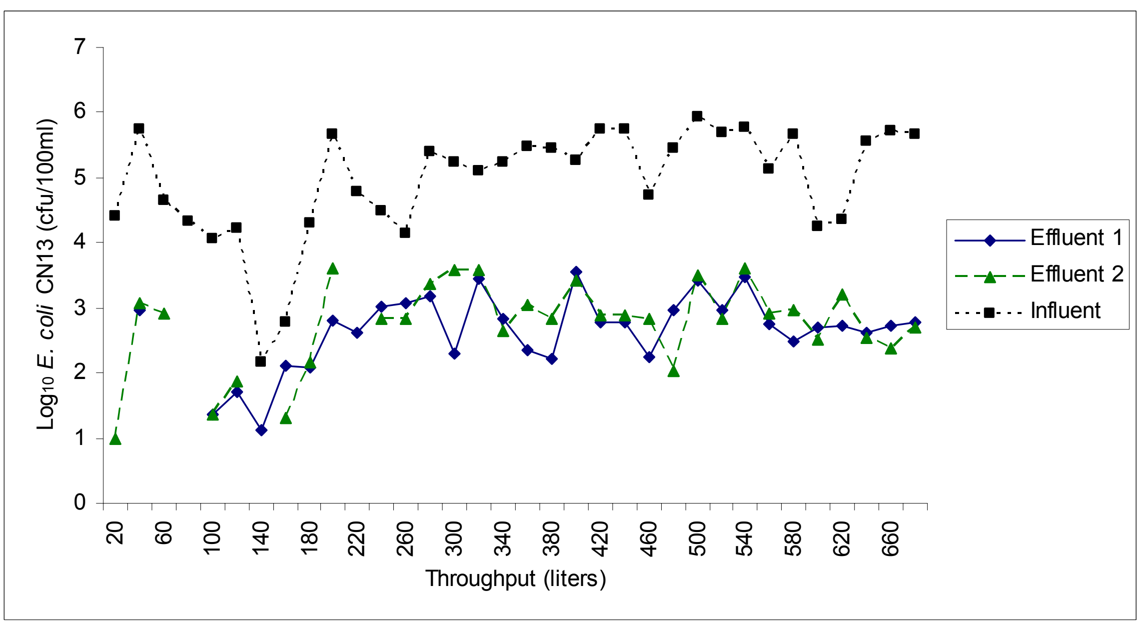

Figure 3.8. Log_{10} concentrations of *E. coli* CN13 in CWP3 (two units run in parallel) against spiked surface water (challenge water B) over 680 l each (total volume 1360 l) (n = 34 sampling events per unit) in both influent and effluent.

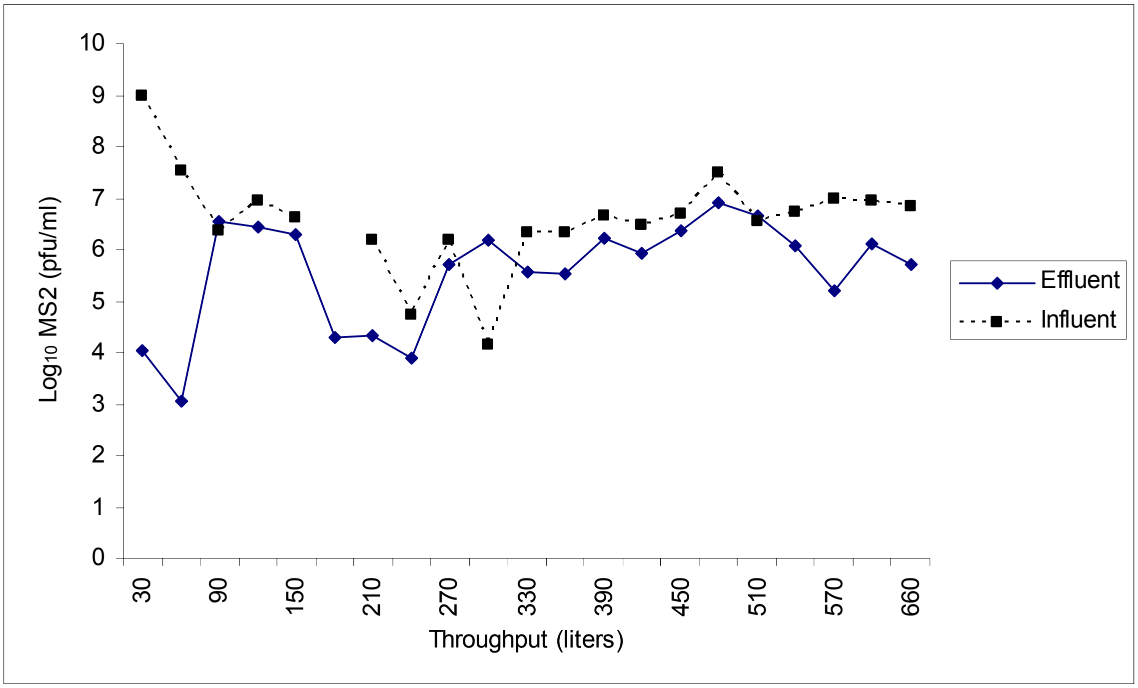

Figure 3.9. Log_{10} concentrations of MS2 in CWP1 against spiked rain water (challenge water A) over 660 l (n = 16 sampling events) in both influent and effluent.

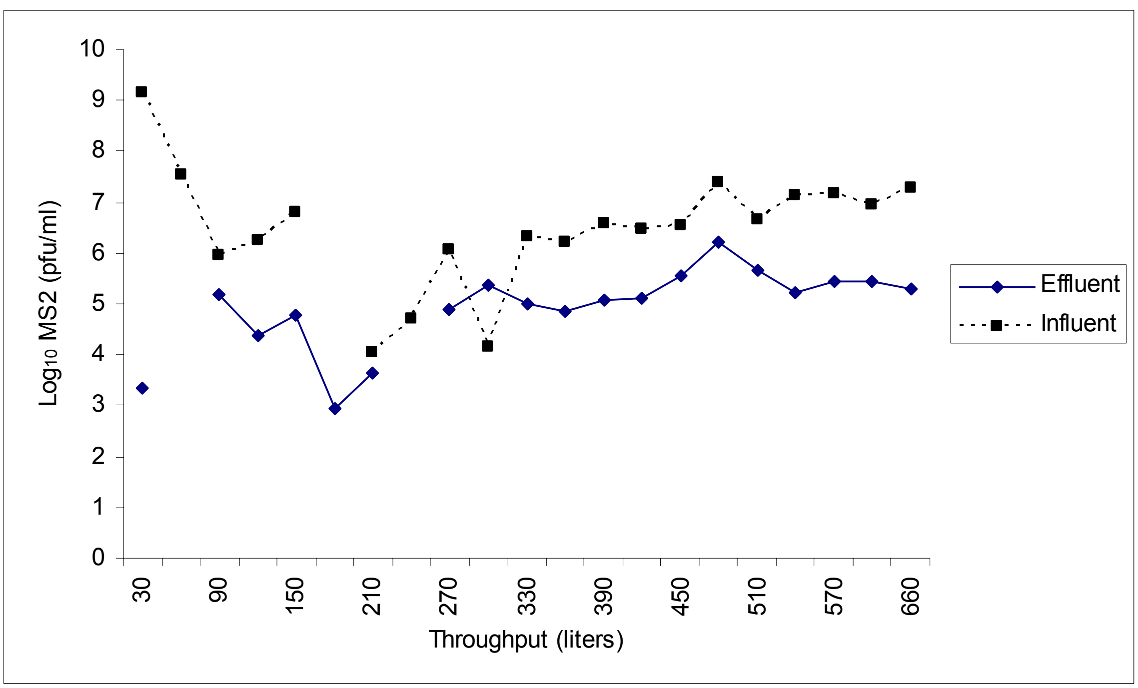

Figure 3.10. Log_{10} concentrations of MS2 in CWP1 against spiked surface water (challenge water B) over 660 l (n = 16 sampling events) in both influent and effluent.

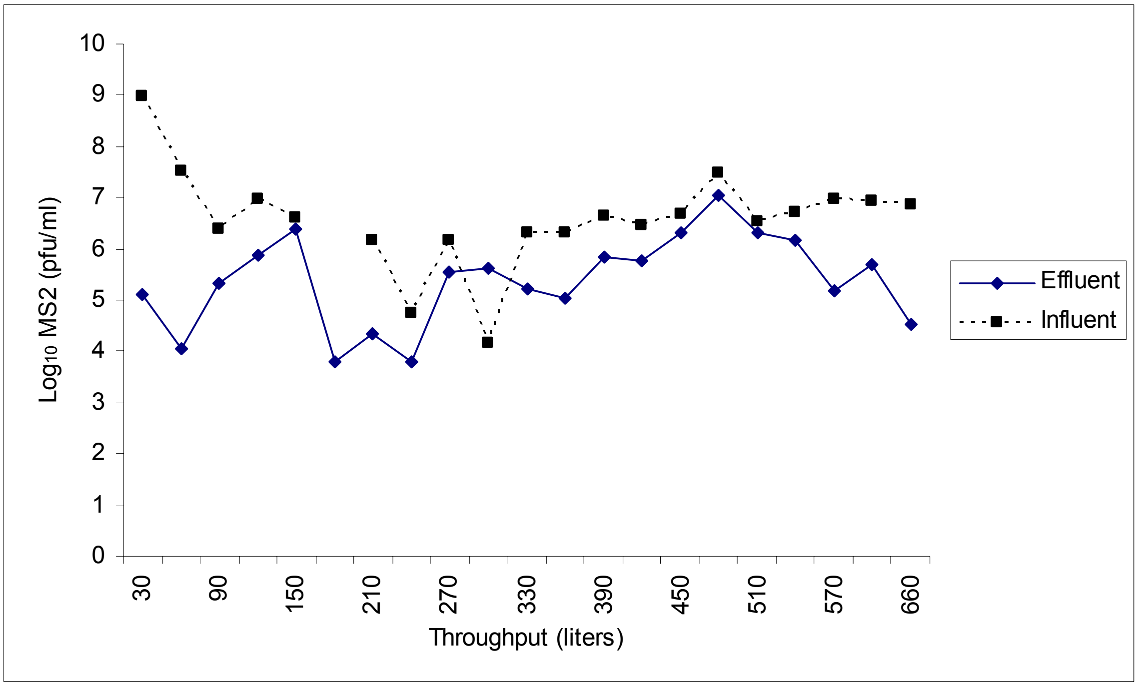

Figure 3.11. Log_{10} concentrations of MS2 in CWP2 against spiked rain water (challenge water A) over 660 l (n = 17 sampling events) in both influent and effluent.

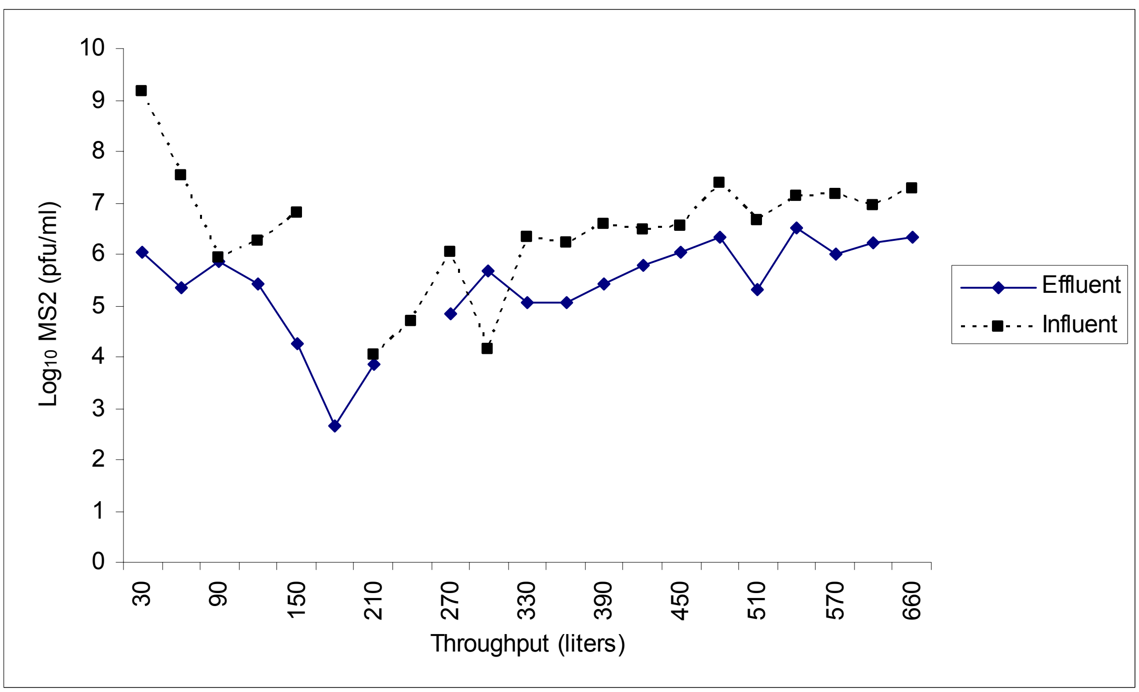

Figure 3.12. Log_{10} concentrations of MS2 in CWP2 against spiked surface water (challenge water B) over 660 l (n = 17 sampling events) in both influent and effluent.

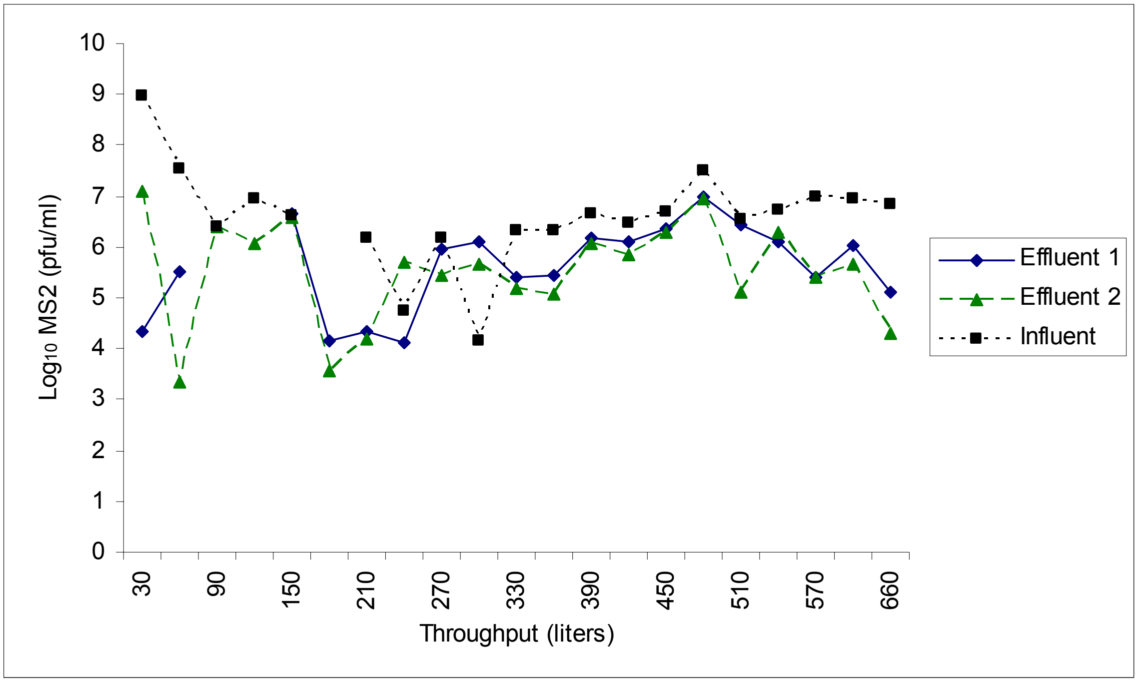

Figure 3.13. Log_{10} concentrations of MS2 in CWP3 (two units run in parallel) against spiked rain water (challenge water A) over 660 l each (total volume 1320 l) (n = 17 sampling events per unit) in both influent and effluent.

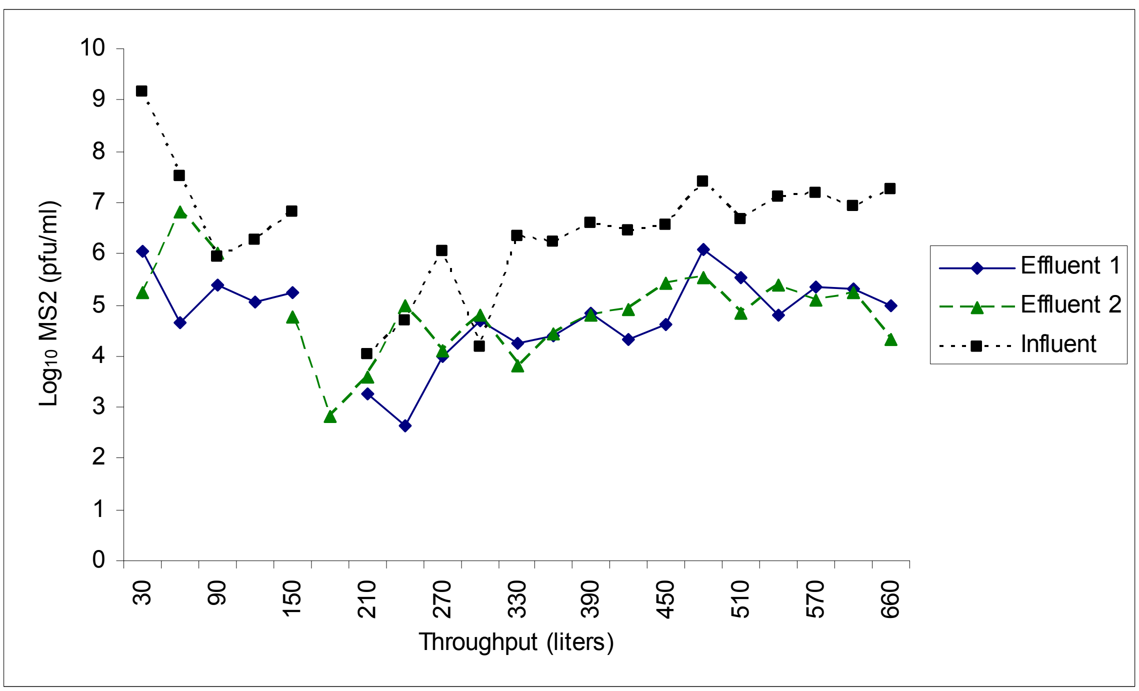

Figure 3.14. Log_{10} concentrations of MS2 in CWP3 (two units run in parallel) against spiked surface water (challenge water B) over 660 l each (total volume 1320 l) (n = 17 sampling events per unit) in both influent and effluent.

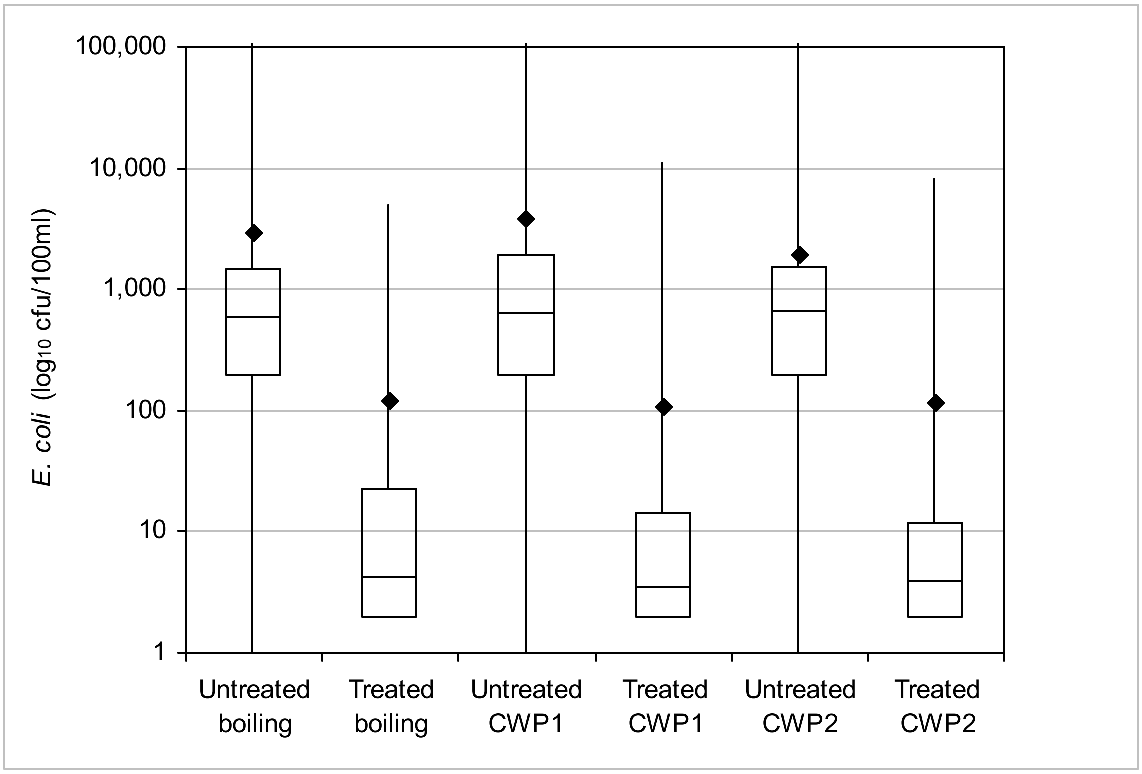

Figure 3.15. Box and whisker plot of *E. coli* counts per 100 ml sample in water treated by boiling, the CWP1, and the CWP2. Boxes indicate 25^{th} and 75^{th} percentile boundaries, the line break within each box represents the median value, and the points are arithmetic means. The upper points represent maxima; minima (<1 *E. coli* cfu per 100 ml sample) are not displayed on this graph (note log scale).

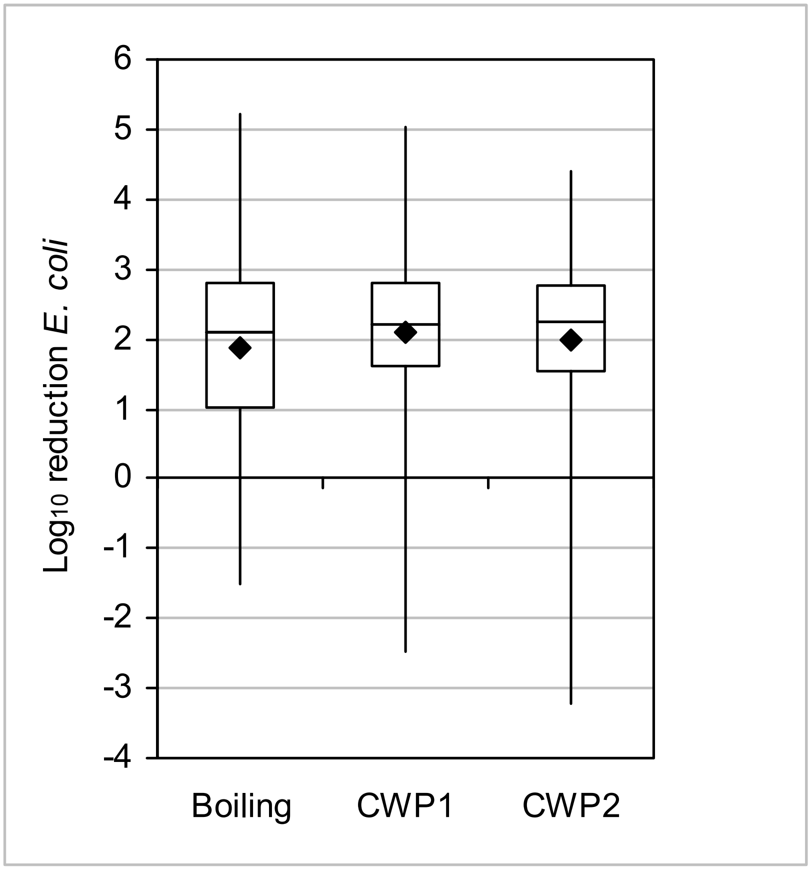

Figure 3.16. Box and whisker plot of *E. coli* $\log_{10}$ reduction sample in water treated by boiling, the CWP1, and the CWP2. Boxes indicate 25th and 75th percentile boundaries, the line break within each box represents the median value, and the points are arithmetic means. The upper and lower points represent maxima and minima.

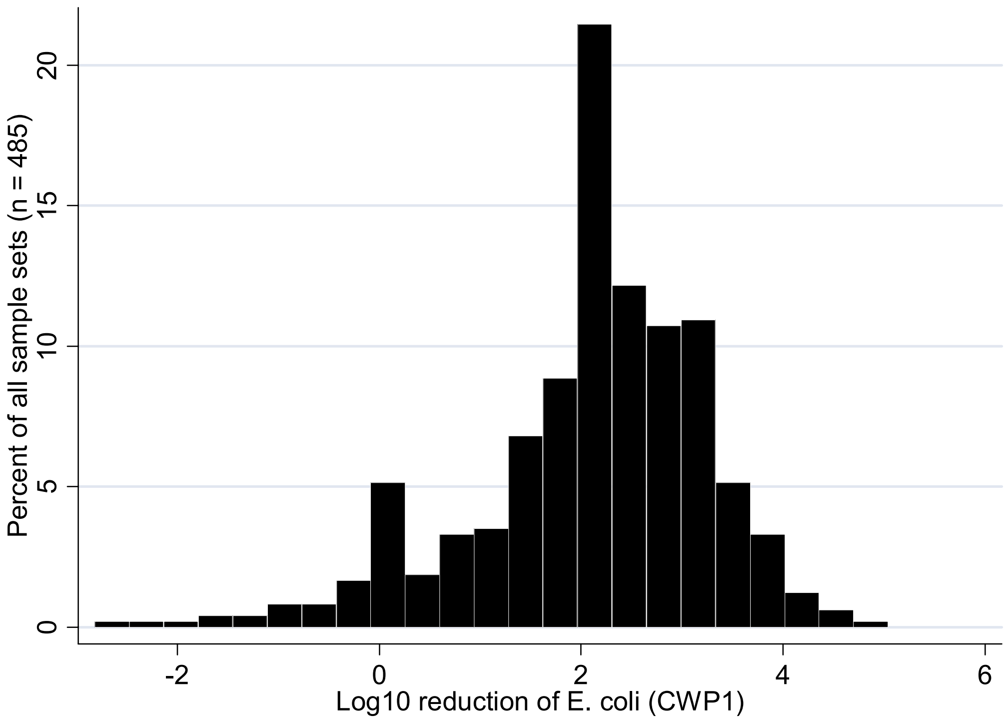

Figure 3.17. Histogram showing the distribution of $\log_{10}$ reduction of *E. coli* in CWP1 filters in field use over the 18 week field trial period. Arithmetic mean: 2.1 (95% CI 2.0-2.2); 24 filters (4.9%) produced water of worse apparent quality than untreated water ($\log_{10}$ reduction of *E. coli* < 0)

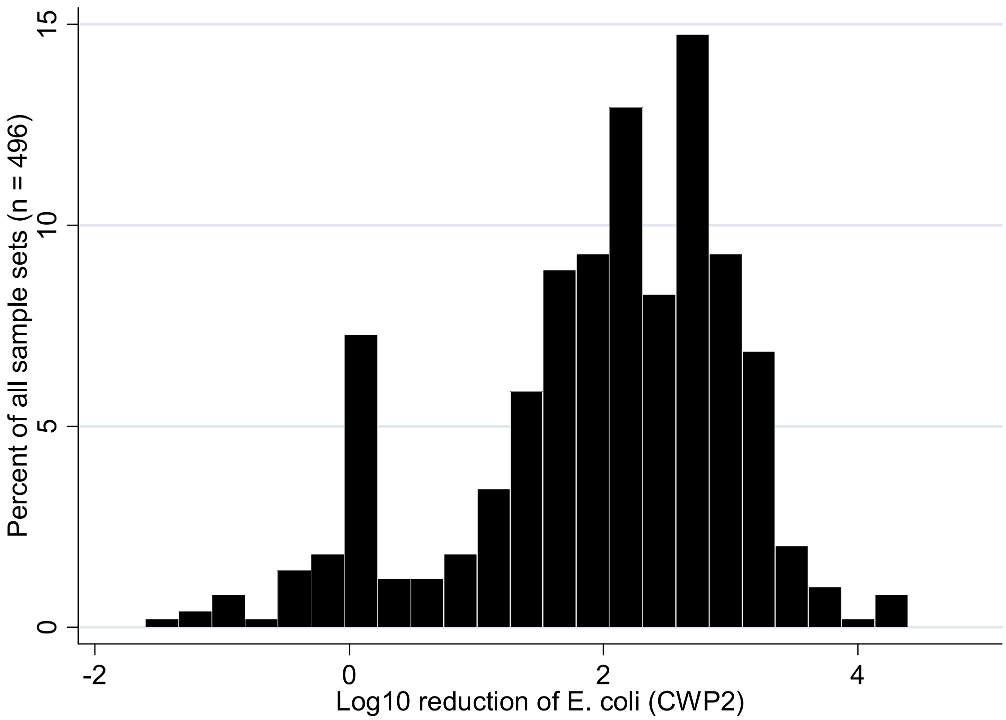

Figure 3.18. Histogram showing the distribution of $\log_{10}$ reduction of *E. coli* in CWP2 filters in field use over the 18 week field trial period. Arithmetic mean: 2.0 (95% CI 1.9-2.1); 25 sample sets (5.0%) produced water of worse apparent quality than untreated water ($\log_{10}$ reduction of *E. coli* < 0)

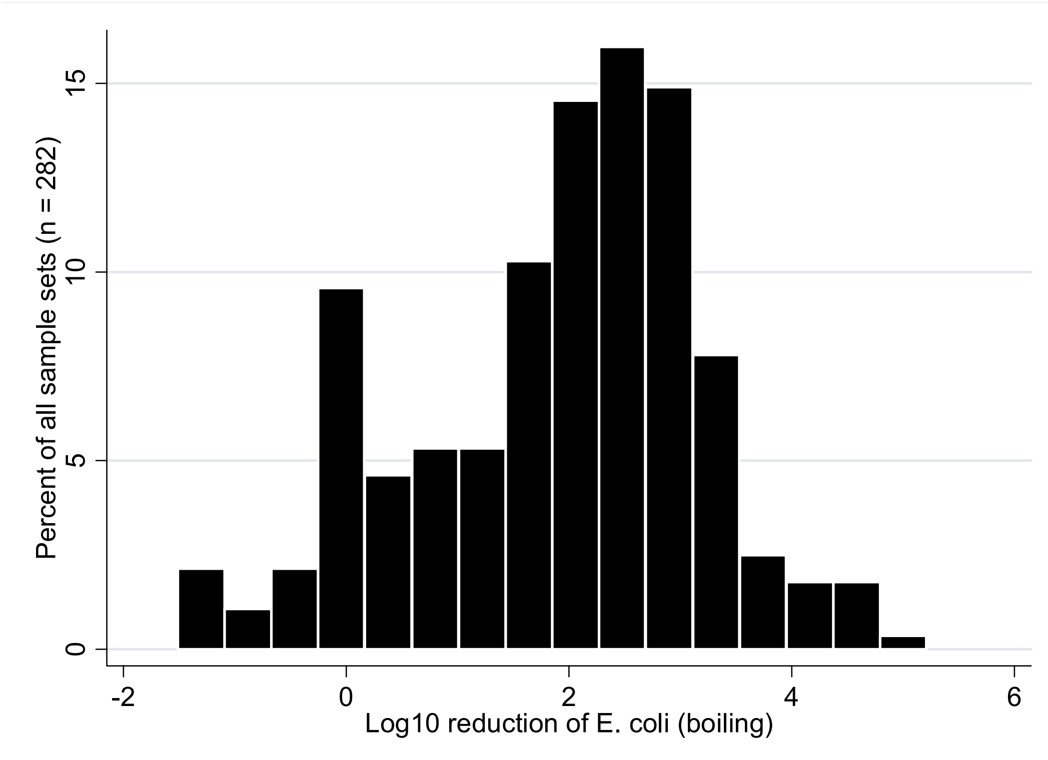

Figure 3.19. Histogram showing the distribution of $\log_{10}$ reduction of *E. coli* by boiling over the 18 week field trial period. Arithmetic mean: 1.9 (95% CI 1.7-2.0); 23 sample sets (8.2%) produced water of worse apparent quality than untreated water ($\log_{10}$ reduction of *E. coli* < 0)

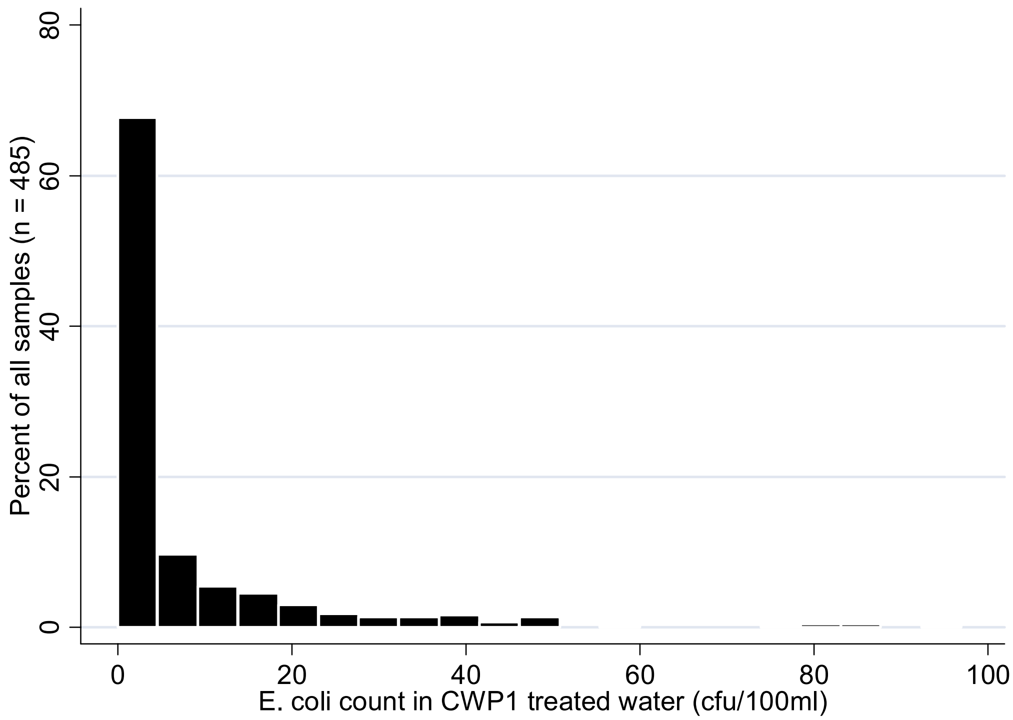

Figure 3.20. Histogram showing the distribution of *E. coli* per 100 ml sample in household drinking water treated by the CWP1. Arithmetic mean *E. coli* counts per 100 ml were 110 (95% CI 41-170) and geometric mean counts were 16 (95% CI 13-20) against arithmetic and geometric mean pre-treatment concentrations of 3800 (95% CI 2200-5400) and 510 (95% CI 420-630), respectively. Note truncated abscissa.

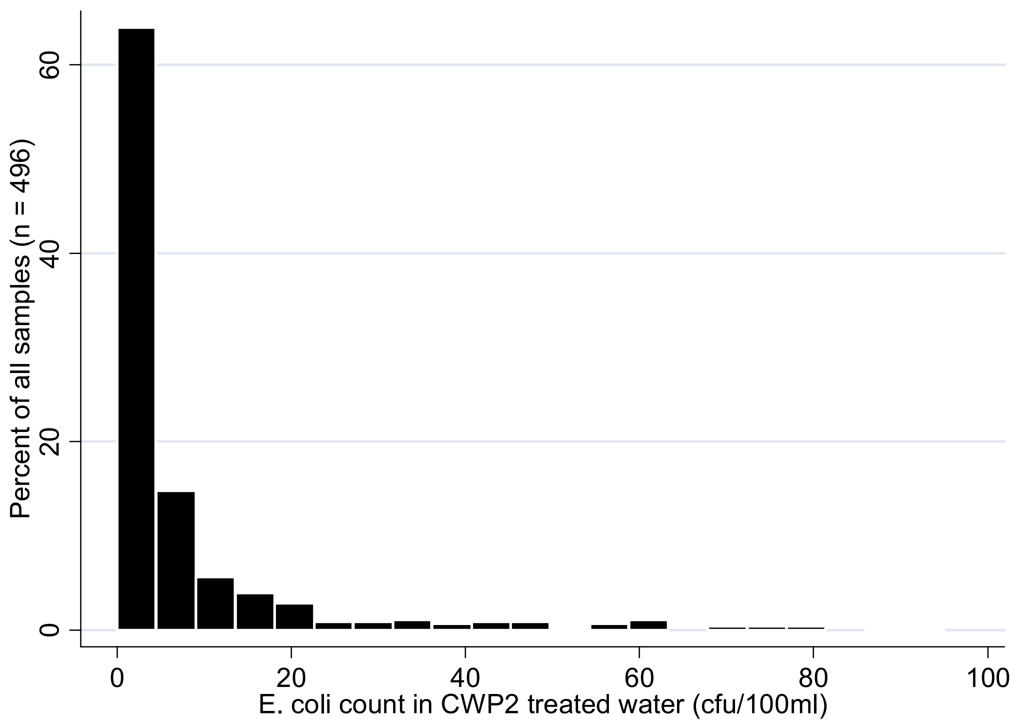

Figure 3.21. Histogram showing the distribution of *E. coli* per 100 ml sample in household drinking water treated by the CWP2. Arithmetic mean *E. coli* counts per 100 ml were 110 (95% CI 57-170) and geometric mean counts were 14 (95% CI 11-18) against arithmetic and geometric mean pre-treatment concentrations of 2000 (95% CI 1300-2600) and 410 (95% CI 340-500), respectively. Note truncated abscissa.

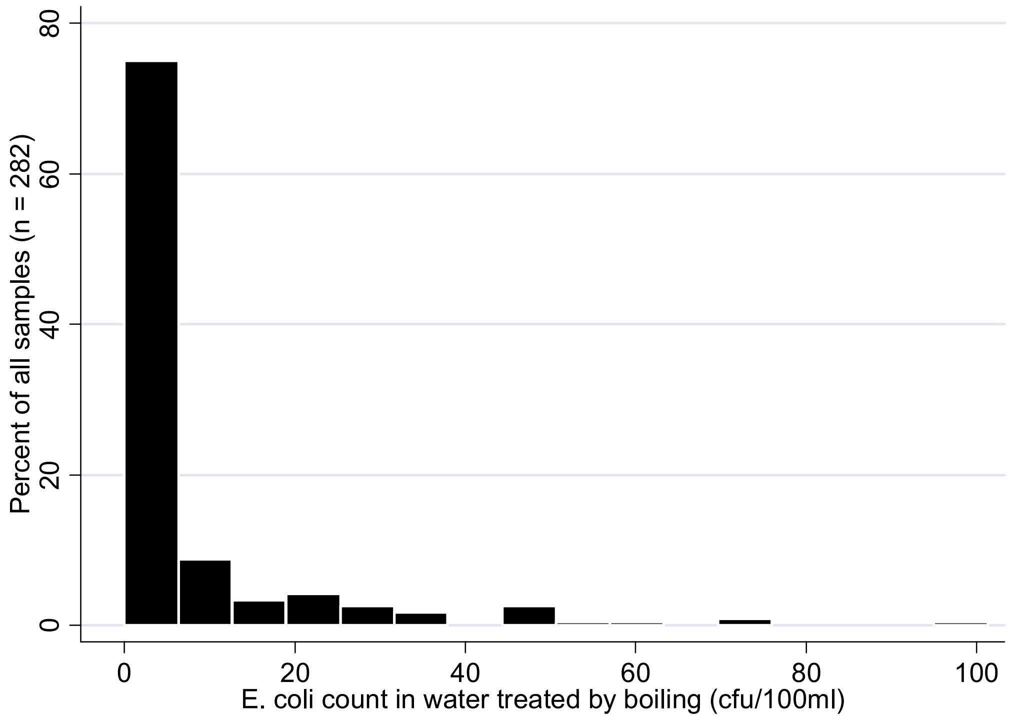

Figure 3.22. Histogram showing the distribution of *E. coli* per 100 ml sample in household drinking water treated by boiling. Arithmetic mean *E. coli* counts per 100 ml were 120 (95% CI 68-170) and geometric mean counts were 24 (95% CI 17-33) against arithmetic and geometric mean pre-treatment concentrations of 2900 (95% CI 1570-4300) and 450 (95% CI 340-580), respectively. Note truncated abscissa.

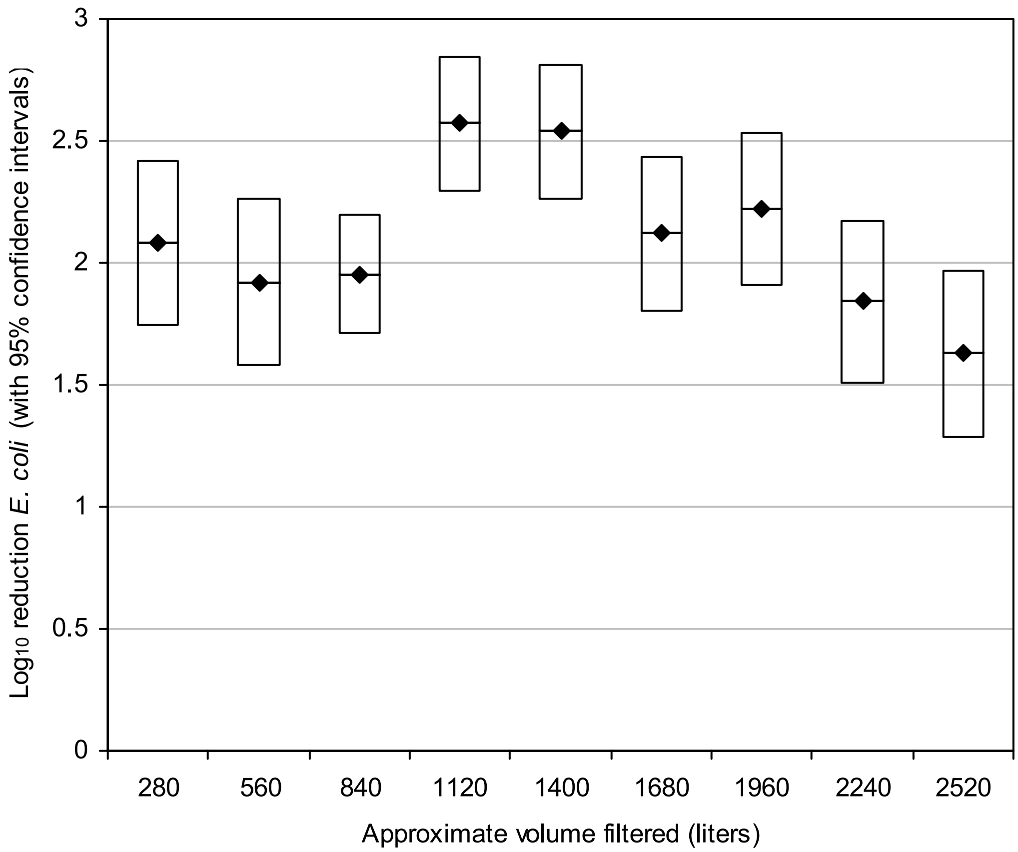

Figure 3.23. Field performance of the CWP1 filter over nine biweekly sampling points, assuming that 20 l per day per household (the mean reported by households) were treated. Points are arithmetic means with bars representing 95% confidence intervals.

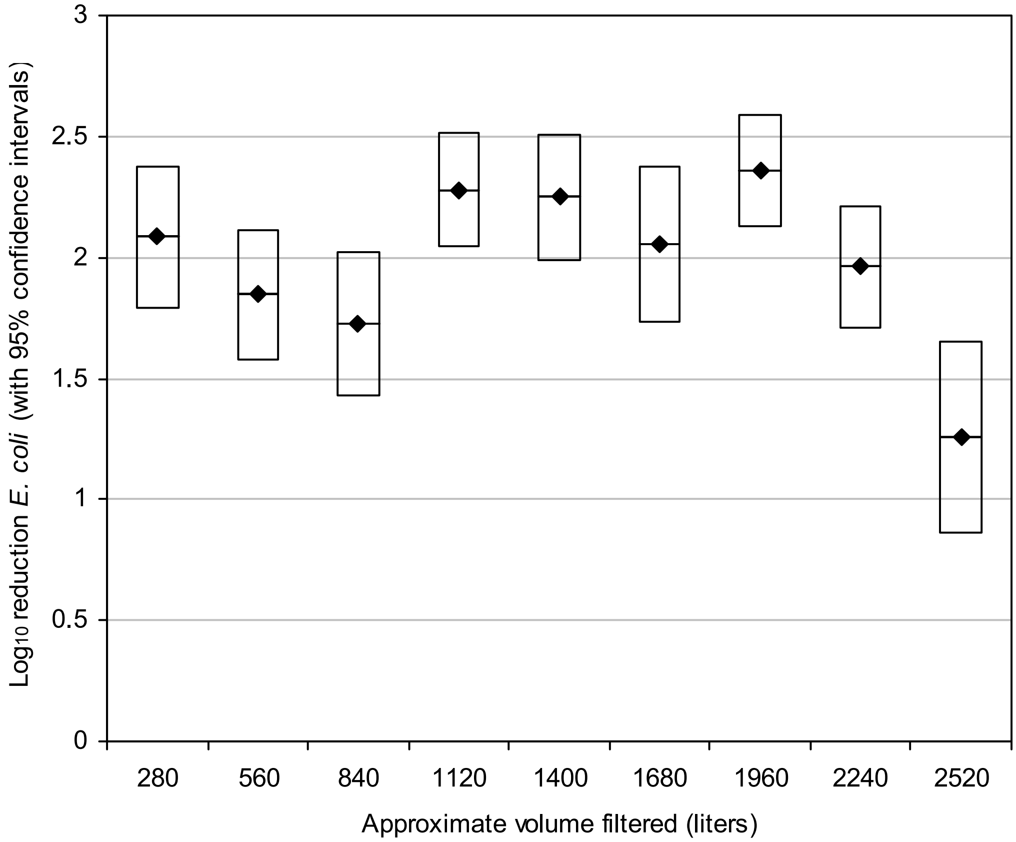

Figure 3.24. Field performance of the CWP2 filter over nine biweekly sampling points, assuming that 20 l per day per household (the mean reported by households) were treated. Points are arithmetic means with bars representing 95% confidence intervals.

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CHAPTER 4: POINT-OF-USE DRINKING WATER TREATMENT IN CAMBODIA: A RANDOMIZED, CONTROLLED TRIAL OF LOCALLY MADE CERAMIC FILTERS

Abstract

Household drinking water treatment has been shown to be an effective intervention to reduce diarrheal diseases in developing countries. Improvements in household drinking water quality and associated health impacts of low-cost ceramic water filters, one promising technology for point-of-use water treatment, have not been adequately characterized. A randomized, controlled intervention trial of two ceramic drinking water filters was conducted in the rural/peri-urban village of Prek Thmey, Cambodia. Interventions were a locally-produced ceramic water purifier (CWP) as manufactured and implemented by the NGO Resource Development International (the CWP1) and a modified version of the filter with high iron oxide content (the CWP2). Major findings were that: (i), the use of either filter resulted in a significant decrease (>40%) in diarrheal disease during the study, an effect that was observed in all age groups and both sexes after controlling for clustering within households and within individuals over time; (ii), the CWP1 filter was associated with a substantial reduction in dysentery (61%), an effect that was not observed with the CWP2; and (iii), there was a positive but weak association between *E. coli* levels measured in drinking water and diarrheal disease outcomes.

4.1 Introduction

4.1.1 Water quality and health

An estimated 1.8 million people die every year from diarrheal diseases (WHO 2004a). The majority of the deaths are associated with diarrhea among children under 5 in developing countries, who are more susceptible to the effects of malnutrition, dehydration, or other secondary health effects associated with these infections. Taken together, diarrheal diseases are the third highest cause of illness worldwide and the third highest cause of death in children worldwide. These are manifested as various types of diarrheal illnesses, from acute syndromes such as cholera and dysentery to extended or chronic illnesses like hemolytic uremic syndrome and Brainerd diarrhea. According to Cambodian national health statistics for the year 2000, the prevalence of childhood diarrhea (children aged 0-60 months) is 18.9%, based on a 14-day recall period. Prevalence in and around Phnom Penh is 24.4% (NIS 2000). National data on diarrhea for older children and adults have not been collected, as children under 5 years represent the most at-risk group and therefore have been the focus of surveys. There were an estimated 309,933 reported cases of diarrhea (including dysentery) in Cambodia in 2000, out of a population of approximately 13 million (WHO 2004a). Data on diarrheal disease morbidity and mortality is often underreported, however, so the true diarrheal disease burden in Cambodia could be appreciably higher.

Prüss *et al.* (2002) estimated that 4.0% of all deaths and 5.7% of the global disease burden are attributable to inadequate water, sanitation, and hygiene, largely due to diarrheal diseases. An unknown percentage of the diarrheal disease burden is due solely to unsafe drinking water, because the viral, bacterial, and parasitic microbes causing diarrheal disease may also be transmitted through contaminated food, hands, fomites, or other routes. We do know, however, that water quality plays an important role in the risk of diarrheal diseases and access to safe water is a major determinant of diarrheal disease rates. Diarrheagenic organisms generally originate in fecal matter and are transmitted through the fecal-oral route of infection (Curtis and Cairncross 2003).

4.1.2 Cambodia and household water treatment

Cambodia is the poorest and least developed country in Asia. For the estimated 66% of Cambodians without access to improved drinking water sources (NIS 2004) and the likely much greater percentage without consistent access to microbiologically safe water at the point of use, household-based water treatment can play a critical role in protecting users from waterborne disease. Surface water in Cambodia is plentiful but often of very poor quality, due in part to inadequate or nonexistent sanitation in rural as well as urban areas. Only 16% of Cambodians have access to adequate sanitation facilities (ibid.). Some groundwater sources in the country are also known to contain high levels of naturally occurring arsenic and other chemical contaminants (Feldman *et al.* 2007; Polya *et al.* 2005). Arsenic in the groundwater is an especially urgent problem in parts of the lower Mekong delta region where there is a high population density. The first cases of arsenicosis in Cambodia were reported in August 2006, in Kandal province (Saray 2006). Surface water and shallow groundwater (often of poor microbiological and aesthetic quality) and rainwater catchment sources (susceptible to contamination during storage) are the principal alternatives to arsenic-contaminated deep wells. If efforts are made to direct Cambodians away from groundwaters contaminated with arsenic, there may be increasing risks of waterborne diarrhea and other infectious diseases resulting from increased use of fecally contaminated surface waters and harvested rainwater.

Due to the poor quality of available drinking water sources and the lack of centralized systems for delivering safe water to households, Cambodia has become a major locus for household water treatment research and implementation. The reality for most Cambodians today is that they must collect water, store it for use in the household, and treat and protect it themselves if they are to have safe water. An estimated 200,000 people (1.5%) already use some form of filtration (sand or ceramic) or chemical treatment at the household level. In addition, many more treat some or all household drinking water using coagulants, traditional cloth filters, or boiling.

Waterborne diseases, in part due to degraded drinking water sources, are a serious public health issue in Cambodia. Cholera, for example, is endemic in Cambodia, with a mean of more than 1000 cases reported per year throughout the country and major localized outbreaks reported in 1998 and 1999 (WHO 2006). Diarrheal diseases are the number one cause of death and disease in children, with prevalence consistently around 20% for a two-week recall period (NIS 2000).

Previous studies document that household-based water treatment and safe storage can provide users with protection against waterborne pathogens where safe water sources and other treatment options are scarce. Recent systematic reviews of field trials established that various household-scale water quality interventions can be effective in reducing the burden of diarrheal disease, with mean reductions of 39% - 44% in users versus non-users (Clasen *et al.* 2006b; Fewtrell *et al.* 2005). Effective household water treatment processes that significantly reduce diarrheal disease include chemical treatments such as chlorination and the use of combined chemical coagulation-flocculation and chlorine disinfection treatments, exposure of water in clear plastic bottles to the UV radiation and heat of sunlight (e.g., the SODIS system), and various forms of filtration (Clasen *et al.* 2006b). Commercially produced porous ceramic filters have been found to not only improve water quality at the point of use but also reduce diarrheal disease in randomized, controlled trials (Clasen *et al.* 2004; Clasen *et al.* 2006a). While studies have documented the performance of these household water treatment technologies for their ability to improve household water microbial quality and reduce diarrheal disease among users, other available technologies documented to be effective for microbial reductions have not been evaluated for their ability to reduce diarrheal disease among users. Such technologies include locally made porous ceramic filters and the biosand filter (an intermittently operated household-scale slow sand filter), both of which are widely promoted and used in Cambodia.

4.1.3 Study overview

The ceramic water purifier (CWP) is an emerging water treatment device that is made locally in Cambodia and in several other developing countries based on a design originally developed in Latin America in the 1980s. Field microbiological effectiveness data as well as health effects of the filters during field use were assessed in a randomized, controlled intervention trial. One hundred eighty households in a rural/peri-urban Cambodian village were initially recruited into the study with informed consent and initially followed for four weeks (two household visits) for the collection of baseline data related to water quality; family health; demographics and socio-economic status; and other water, sanitation, and hygiene (WSH)-related factors. Then, households were randomly assigned to one of three groups: those receiving the standard CWP (referred to here as the CWP1) as implemented by NGOs in Cambodia, those receiving a modified CWP (referred to as the CWP2) developed in our laboratory at UNC and fabricated in Cambodia by the same factory that made the CWP1, and a control group (no intervention). Households were then followed for 18 weeks with biweekly visits (nine visits per household). At each household visit, treated and untreated water samples were taken and analyzed for *E. coli* using membrane filtration and diarrheal disease and other health data were collected for all family members. A variety of longitudinal water, sanitation, and hygiene data were collected as well using interviews with household members and by direct observation. This study was approved by the Biomedical Institutional Review Board of the UNC Office of Human Research Ethics and the Cambodian Ministries of Health and Rural Development.

Stratified analyses and log-risk regression with Poisson extension of generalized estimating equations (GEE) were employed in analysis of water quality and health impact data to assess the interventions' effectiveness against diarrheal disease in the study group.

4.2 Purpose and objectives

The purpose of this study was to evaluate the health impacts of the CWP1 and CWP2 filters in field use in a Cambodian village. Reduction of diarrheal disease in children under five years of age was the principal outcome of interest. The study hypothesis was that in households using the ceramic filters (of either type), diarrheal disease in the intervention cohort (using filter interventions) would be ≥20% less than in control households (without access to a filter) based on longitudinal prevalence and incidence measures. The bases for this detectable level of diarrhea reduction were the meta-analyses by Fewtrell *et al.* (2005) and Clasen *et al.* (2006b, 2007), which conclude that POU water quality interventions can substantially reduce diarrheal disease in users versus non-users, by a mean of approximately 30 - 40%.

The specific objectives of this study were to:

- assess impacts of the two filters on diarrheal disease (including dysentery) in households using them against a control group;
- determine whether important differences exist in the diarrheal disease impact of the two filters;
- examine other water, sanitation, and hygiene-related factors and their impact on diarrheal disease; and
- examine the relationship between household water quality and diarrheal disease (including dysentery) in all households.

4.3 Methods and materials

4.3.1 The intervention filters

This study examines the field effectiveness of two filters: that manufactured and promoted in Cambodia by Resources Development International (RDI) in Kandal Province beginning in December 2003 (the CWP1) and a modified version of the same using goethite-amended base clay (CWP2). This study assesses water quality (with microbiological quality and turbidity as exposure variables) and health impacts (based on diarrhea and dysentery as outcome variables) of these interventions over eighteen weeks *in situ*.

The ceramic water purifier manufactured by RDI (CWP1) is a porous ceramic pot-style filter based on the ICAITI model promoted by Potters for Peace. The filters have been made in Kandal Province at a central factory since 2002. Raw clay is milled and mixed with ground rice husks, press molded, and fired to cone 012 (~870^{o}C) in a large kiln using scrap wood pieces as fuel. After flow testing (a quality control step) to ensure that the flow rate is in the proper range to indicate target pore size and structure (1-3 l per hour), the porous filters are painted with a 0.00215 molar reagent-grade (99.999%) $AgNO_3$ solution intended to inhibit microbial growth on the filter. Approximately 300 ml are applied to each filter: 200 ml on the inside (46 mg Ag) and 100 ml on the outside of the filter (23 mg Ag).

The CWP2 is a modified version of the RDI (CWP1) filter that contains a higher percentage of iron oxide-rich clay (1:6 FeOOH:base clay by dry weight), based on prototype testing that suggested greater effectiveness of these filters against viruses (geometric mean >99.99%) in initial testing over limited volumes of spiked challenge waters. Other details of manufacture are identical to the standard filter. The CWP2 is also coated with a silver nitrate solution by the same method as the CWP1.

4.3.3 Study site

All households were located in Prek Thmey village, Kandal Province, Cambodia, approximately 10km from Phnom Penh along the Bassac river. The wastewater from Phnom Penh flows into the Bassac river approximately four kilometers upstream of the study area. Surface water, including heavily impacted Bassac river water, is the principal source of drinking water in this community. Rain water harvesting is also practiced when possible, which is primarily during the rainy season.

4.3.4 Study population and selection of households

The study population consisted of all households in the peri-urban/rural village of Prek Thmey, Cambodia. GPS coordinates or other locating details were obtained for all village households, and households were selected at random using a random numbers table. Three hundred (300) households were randomly selected to be approached by the study team to assess eligibility for the study. Inclusion criteria for the study were that households (i) were willing to voluntarily participate, (ii) are in the village of Prek Thmey as defined in the initial survey, (iii) store water in the home, (iv) have a child of less than 5 years of age as a household member at the first household visit, and (v) did not use commercial bottled water as the primary source of household potable water. Exclusion criteria were: (i) unwillingness to participate, (ii) no child less than 5 years of age in the household at the time of the first household visit, (iii) primary or exclusive use of commercial bottled water as potable water in the home.

Households were approached in cluster-randomized order (cluster size=10 households) and eligible households were asked to enroll in the study. Households were approached until 180 households were enrolled in the study via informed consent and in accordance with IRB approval from the University of North Carolina-Chapel Hill Office of Human Research Ethics and Cambodian Ministry of Health approval for ethical human research.

After a baseline data collection period of 4 weeks (two sampling rounds for all households), households were randomized to one of three treatment arms: (i) those receiving the ceramic water purifier (referred to as "CWP1") as produced by Resource Development International (RDI), (ii) those receiving a CWP2 filter with metal oxide additive, also produced by RDI, and (iii) a control group receiving no filter.

4.3.5 Inducements to participate

All subject households were provided with *gratis* water filters (a CWP, as the more proven and established technology) and storage containers upon completion of the study (after all household interviews and water samples were collected) as part of their willingness to participate in the study, together with training on use and maintenance of the filter. Households were also supplied with several packets of UNICEF soluble oral rehydration salts at each household visit, regardless of whether households reported diarrheal disease.

4.3.6 *A priori* sample size and power calculations

A demographic and health survey in the study village by RDI-Cambodia indicated that 41% of the population was under 16 years of age and that the baseline diarrheal disease prevalence for this group was 16%. National statistics indicate that the prevalence of diarrhea in the Phnom Penh area for children under 5 is 24.4% (NIS 2000). Based on recent systematic reviews by Fewtrell *et al.* (2005) and Clasen *et al.* (2006b), which found mean reductions in diarrheal disease resulting from household water quality interventions to be near 40%, we based our sample size calculation on the detection of a longitudinal prevalence proportion ratio of 0.80 (that is, detection of a 20% reduction in longitudinal prevalence of diarrheal disease experienced by intervention and control groups). This detectable difference of 20% is considered to be conservative, based on data published by International Development Enterprises – Cambodia (Roberts 2004), indicating that the CWP was associated with a 41% decrease in diarrhea among all users versus non-users (26% among women, 55% among men) in an initial study of the intervention.

The sample size for the study was computed as approximately 300 individuals (in each group) to detect a 20% difference in proportions between the study groups with 80% power and $\alpha = 0.05$, using the methods for analysis of binary outcomes in multiple groups with repeated observations as described by Diggle *et al.* (2002). Calculations account for limited clustering within households and clustering in individuals over time, which are potentially important in the analysis of diarrheal disease data (Leon 2004; Killip *et al.* 2004). Results of power analyses in EpiSheet and EpiInfo were in general agreement with these results.

4.3.7 Randomized controlled trial

The randomized controlled trial consisted of 60 households in each of three groups: those using the CWP, those using the CWP2, and a control group (no filter). Participating households were visited eleven times for water sample collection and analyses altogether; nine of these visits were post-baseline (after randomization). Data on water use and handling practices, sanitation and hygiene, and other potentially important covariates were gathered during the baseline period and at each subsequent visit.

4.3.8 Informed consent

Informed consent was obtained from the appropriate family member. This was the head of household (defined as the primary caretaker for the children, responsible for household work and either responsible for or knowledgeable of household water management practices, usually an adult female) who acted as the main correspondent for the home in subsequent visits. This person was identified by asking to speak with the person who is the primary care taker and in charge of household responsibilities such as water management, cooking, cleaning, etc. The consent form was translated into Khmer and then back translated into English, and piloted to ensure clarity before use in the field. Subjects read or were read the form in Khmer by project staff. Participating householders were presented with a narrative description of the project (both written and orally) and asked to participate in the study entailing up to eleven (11) household visits by the project team. Participants then signed the consent form, representing consent for all of the persons in the house. This project and its means for obtaining informed consent from participants were reviewed and approved by the Biomedical Institutional Review Board on Research Involving Human Subjects, Office of Human Research Ethics, The University of North Carolina at Chapel Hill, USA, and the Ministry of Rural Development, Kingdom of Cambodia.

4.3.9 Data collection

All survey instruments were prepared in both English and Khmer prior to use in the study. They were pre-structured and pre-tested (by back-translation from Khmer to English and use in pilot interviews). The project manager, project coordinator, and health specialist took responsibility for preparing all survey instruments. Surveys used simple, straightforward language with predominantly closed (multiple choice) questions.

The data collection (field) team was composed of four interviewers who were native speakers of Khmer and had related experience in community health data collection in the study area. During the months of June to October 2006, the data collection team visited participating households eleven times (bi-weekly, four week baseline period and eighteen week intervention period). The primary caregiver was asked to provide a 7-day binary recall of diarrheal disease for herself and all members of the household. Diarrhea was defined as three or more loose or watery stools in a 24-hour period Diarrhea with blood indicated dysentery. Discrete cases or case duration data were not collected.

4.3.9.1 Data entry and management

Survey data were collected via verbally administered questionnaires and recorded onto hard copy data sheets. Households and individuals were assigned a unique code number as an identifier. During sample collection, household surveys and water samples were identified by the unique household code number assigned by the data collection team. Data were collected and original data sheets were stored at the laboratory office in bound notebooks in a locked cabinet with access only to specifically authorized project staff. Surveys and water quality data were entered into a Microsoft Excel spreadsheet or

Microsoft Access database and copied into Stata version 8.1, excluding the direct personal identifiers of the study participants. All data were entered twice by separate data entry staff and compared to minimize data entry mistakes.

4.3.9.2 Water quality data

Water samples of 250 ml volume were taken from each household in the study at each household visit to measure concentrations of fecal indicator bacteria and turbidity in untreated and treated household drinking water. Samples were kept cool and transported as soon as possible to the laboratory in Kien Svay, where analysis was performed as soon as possible, in all cases within 24 hours. Total coliforms and *Escherichia coli* were quantified in water samples using membrane filtration (MF) followed by incubation on selective media for colony formation and reported as colony-forming units (cfu) per 100 ml. All samples were processed in duplicate using a minimum of two dilutions and positive and negative controls. Households in the intervention group were sampled for two types of water: untreated, stored household water and treated water as it was delivered via the filter tap. Samples from the control households were taken for analysis as well, and included their current drinking water and untreated water, if they used another water treatment method (e.g., boiling). Turbidity of water samples was measured in triplicate using a turbidimeter (Hach Pocket®) and the average values reported as NTU. pH of water samples also was measured in the laboratory using an electronic pH meter (Thermo Orion 290A+).

4.3.9.3 Other exposure variables

In addition to the household data collected on health and water quality, additional data on potential covariates were collected during household visits. Questions were asked to determine compliance with the household water intervention (water acquisition, treatment, storage, and use practices) and to document sanitation and hygiene conditions and practices. The collected hygiene, sanitation, and water use data can be correlated with water quality and health data as potential covariates in the subsequent analysis. A variety of socio-economic data were collected on each household as potential covariates in the analysis. Observational data, such as presence of soap in the home, data on types and numbers of water storage containers, details on family filter use, presence of animals or animal waste in the home, were used to supplement and verify survey data collected in interviews.

4.3.10 Analytical approach

4.3.10.1 Exposures and outcomes

Water quality, health, and other household data were initially used in stratified analyses to identify trends for key exposure and outcome variables. Exposure variables of interest were presence of an intervention (CWP1 or CWP2), water quality measures including *E. coli*/100 ml in household drinking water, and other measured covariates related to water, sanitation, and hygiene. Key outcome variables were diarrheal disease in all individuals and in children under five years of age (0-48 months at the first household visit). Dysentery, or diarrhea with blood, was also measured for all individuals and was a subset of all diarrheal disease.

4.3.10.2 Regression and confounding

Regression models were used to analyze diarrheal disease (bloody diarrhea and all diarrhea) prevalence proportions by exposure status. Potentially confounding variables in the analytical model were (i) those that affect the exposure in the study population (e.g., factors associated with continued use of the filter); and (ii) those that are risk factors for the outcome of diarrheal disease in the control group (Last 2001). Confounders were identified based on an *a priori* change-in-effect criterion of 10%. Stratified and adjusted pooled estimates for health effect measures were reported. All analyses were performed in Stata Version 8.1 (StataCorp, College Station, TX).

4.3.10.3 Effect measure estimation for outcomes

Stratified analyses and log-risk regression with Poisson extension of generalized estimating equations (GEE) were employed in analysis of time series data to determine the effect of the interventions and water quality in the home on diarrheal disease (both bloody and non-bloody diarrhea) as described below. Prevalence proportion ratios for diarrheal disease based on a 7-day recall period among members of households with (intervention) and without (non-intervention or control) filters were used as the main outcome; analyses were performed using each intervention against the control group. Incidence rate ratios were also estimated from the prevalence proportion ratios based on case frequency and duration assumptions as described below.

4.3.10.4 Generalized estimating equations

To control for clustering of the outcomes within households and within individuals over time, a Poisson extension of generalized estimating equations (GEE) was employed in log-linear regression. GEE methods for analyzing binary outcomes over multiple time points were first described by Zeger and Liang (1986) and Liang and Zeger (1986). The model uses the marginal expectation (average response for observations with the same covariates) as a function of covariates in the analysis; correlation between individual observations is computed via a variance estimation term. The GEE model assumed that missing observations are Missing Completely at Random (MCAR) as described by Little and Rubin (2002): that the probability of an observation being missing is not related to measured or unmeasured cofactors that may be related to the exposure or the outcome. The GEE model and its application to binary longitudinal data accounting for correlation is fully described by Diggle *et al.* (2002).

4.3.10.5 Longitudinal prevalence proportion ratios

The measure of diarrheal disease risk in this study was the longitudinal prevalence ratio, the proportion of total observed time with the disease outcome in individuals. The mean longitudinal prevalence for the group is also the proportion of time with the outcome divided by the total observed time, if all group members are followed for an equal number of days (Schmidt *et al.* 2007). Because not all individuals were followed for the same amount of time in this open cohort due to missing observations, loss to follow up, death, and birth, longitudinal prevalence for individuals whose records comprised less than the 63 days of post-baseline observation were computed on a weighted basis. Because a seven day recall period was used at each household visit and no data were collected on case duration or frequency, the longitudinal prevalence calculation for individuals had a resolution of seven days.

Longitudinal prevalence is a diarrheal morbidity measure that has been shown to be strongly correlated with risk of mortality in children under 5 years of age (Morris *et al.* 1996; Schmidt *et al.* 2007). Longitudinal prevalence may be better correlated with nutritional status than incidence measures (Morris *et al.* 1996; Schmidt *et al.* 2007). Longitudinal prevalence measures also possess practical and analytical advantages over incidence measures, since case frequency and duration data (often difficult to obtain) are not collected (ibid.; Baqui *et al.* 1991; Morris *et al.* 1994). For these reasons, an increasing number of studies incorporate this measure in intervention trials (e.g., Chiller *et al.* 2006; Crump *et al.* 2004a, 2004b; Luby *et al.* 2006).

The analytical model produces estimations of longitudinal prevalence proportions that are computed from binary recall data. Estimates for longitudinal prevalence were adjusted for clustering within households and in individuals over time using a Poisson extension of Generalized Estimating Equations (GEE) as described previously. The prevalence proportion ratio (PPR) was then computed as the diarrheal prevalence proportion in this intervention group divided by the prevalence proportion in the control group.

4.3.10.6 Incidence rate ratios

Incidence rate ratios were also estimated for outcomes of diarrheal disease and diarrheal disease with blood based on assumed case durations of three days for acute diarrheal disease and seven days for bloody diarrhea and one case per seven day period for either outcome. Person time at risk was then computed as four days if an episode of diarrheal disease was reported, zero days if a case of bloody diarrheal disease was reported, and seven days if no cases were reported for that seven day period. Computed incidence rate ratios based on these assumptions and prevalence proportion ratios were close approximations of the other.

4.4 Results

4.4.1 Study participants and households

Demographic and other characteristics of the households included in the longitudinal study are presented in Table 4.1, by study group. One hundred eighty (180) households participated in the study, with a total of 1196 people (mean household size: 6.6, median age: 19, range: 0-105 years at the time of first household visit. Because having a child ≤5 years of age was a longitudinal study inclusion criterion for households, the age distribution in the three groups may not be representative of the source population in the study village; 249 individuals (21%) were children under age 5 at the start of the study. Four households (2%) were lost to follow up, two in each intervention group.

4.4.2 Data stratified by study group

The CWP1 intervention group contained 60 households and 395 individuals (6.58 people per household, 53% female, 22% under the age of five at the start of follow-up). Respondents were asked more detailed questions about socioeconomic factors (including a direct estimate of monthly household income) and education for the primary caregiver in the household. Reported total household income in 5 (8% of) households was <$50, in 16 (27% of) households $50-$99, in 24 (41% of) households $100-$149, and in the remaining 14 households (24%) ≥$150. One household (2%) declined to answer. Education levels for the primary caregiver (usually an adult female) in the CWP intervention group were reported as: 13 (22%) had no formal schooling, 38 (63%) had some or all primary school, 6 (10%) had some or all secondary school, and 3 (5%) had post-secondary or vocational training.

The CWP2 intervention group contained 60 households and 398 individuals (6.63 people per household, 53% female, 20% under the age of five). Respondents were asked more detailed questions about socioeconomic factors (including a direct estimate of monthly household income) and education for the primary caregiver in the household. Reported total household income in 10 (17% of) households was <$50, in 21 (36% of) households $50-$99, in 18 (31% of) households $100-$149, and in the remaining 10 households (17%) ≥$150. One household (2%) declined to answer. Education levels for the primary caregiver (usually an adult female) in the CWP2 intervention group were reported as: 10 (17%) had no formal schooling, 28 (47%) had some or all primary school, 22 (37%) had some or all secondary school, and none had post-secondary or vocational training.

The control group (without filters) contained 60 households and 403 individuals (6.72 people per household, 52% female, 20% under the age of five). Respondents were asked more detailed questions about socioeconomic factors (including a direct estimate of monthly household income) and education for the primary caregiver in the household.

Reported total household income in 5 (8% of) households was <$50, in 25 (42% of) households $50-$99, in 18 (30% of) households $100-$149, and in the remaining 12 households (20%) ≥$150. Education levels for the primary caregiver (usually an adult female) in the control group were reported as: 15 (25%) had no formal schooling, 27 (45%) had some or all primary school, 17 (28%) had some or all secondary school, and 1 (2%) had post-secondary or vocational training.

4.4.3 Water use and handling practices: baseline

All households were asked about water use and handling practices both as part of baseline data collection and in subsequent household visits; baseline data are given here. CWP1 intervention households were asked about water use and handling practices, hygiene and sanitation, and other potentially important covariates. Results are presented in Table 4.1. The study spanned both dry and wet periods (June – October 2006). When water is more available (wet season), 33 households (55%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 26 (43%) reported use of a deep well (defined here as ≥10m in depth); 1 (2%) used a shallow well; and 44 (73%) used stored rainwater. When water is less available (dry season), 37 households (62%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 27 (45%) reported use of a deep well (defined here as ≥10m in depth); none used a shallow well; and 2 (3%) used stored rainwater from the previous rainy period. Twenty-eight (47%) used one or more uncovered water storage containers. Respondents were asked to demonstrate to the interviewer the usual method of collecting water from the container for drinking; 36 (60%) of respondents dipped hands or a cup directly into the container, while 24 (40%) used a tap or a dipper which was then poured out into a cup for drinking.

CWP2 intervention household data are presented in Table 4.1. When water is more available (wet season), 31 CWP intervention households (52%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 28 (47%) reported use of a deep well (defined here as ≥10m in depth); none used a shallow well; and 39 (67%) used stored rainwater. When water is less available (dry season), 31 CWP2 intervention households (52%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 30 (50%) reported use of a deep well (defined here as ≥10m in depth); none used a shallow well; and none used stored rainwater. Twenty-seven (45%) used one or more uncovered water storage containers. Respondents were asked to demonstrate to the interviewer the usual method of collecting water from the container for drinking; 20 (33%) of respondents dipped hands or a cup directly into the container, while 40 (67%) used a tap or a dipper which was then poured out into a cup for drinking.

Control household (without filters) data on water use and handling are presented in Table 4.1. When water is more available (wet season), 27 control households (45%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 29 (48%) reported use of a deep well (defined here as ≥10m in depth); none used a shallow well; and 44 (73%) used stored rainwater. When water is less available (dry season), 33 control households (55%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 29 (48%) reported use of a deep well (defined here as ≥10m in depth); none used a shallow well; and 1 (2%) used stored rainwater from the previous rainy period. Twenty-six (43%) used one or more uncovered water storage containers. Respondents were asked to demonstrate to the interviewer the usual method of collecting water from the container for drinking; 27 (45%) of respondents dipped hands or a cup directly into the container, while 23 (38%) used a tap or a dipper which was then poured out into a cup for drinking.

4.4.4 Sanitation and hygiene practices: baseline

Of the 60 households in the CWP1 intervention group, 31 (52%) had access to sanitation (either the household's own or a shared latrine). None of the households was connected to a conventional sewerage system. Respondents were asked whether and how often they and members of their family washed their hands, for example after defecating and before preparing food. Of the 60 households, 32 (53%) of respondents indicated that hand washing was practiced by all members of the household "always" at critical points with soap and water. Respondents were also asked to demonstrate that there was soap in the household at the time of the visit; 50 CWP intervention households (83%) were able to produce it.

Of the 60 households in the CWP2 intervention group, 31 (52%) had access to sanitation (either the household's own or a shared latrine). None of the households were connected to a conventional sewerage system. Respondents were asked whether and how often they and members of their family washed their hands, for example after defecating and before preparing food. Of the 60 households, 32 (53%) of respondents indicated that hand washing was practiced by all members of the household "always" at critical points with soap and water. Respondents were also asked to demonstrate that there was soap in the household at the time of the visit; 52 CWP2 intervention households (87%) were able to produce it.

Of the 80 households in the control group, 33 (56%) had access to sanitation (either the household's own or a shared latrine). None of the households were connected to a conventional sewerage system. Respondents were also asked whether and how often they and members of their family washed their hands, for example after defecating and before preparing food. Of 80 household respondents, 35 (58%) indicated that hand washing was practiced by all members of the household "always" at critical points with soap and water. Respondents were also asked to demonstrate that there was soap in the household at the time of the visit; 50 control households (83%) were able to produce it.

4.4.5 Water quality data

Filters were able to supply high quality (low risk) drinking water to users: 59% of CWP1 filter effluent samples were under 10 *E. coli*/100 ml, with 40% of samples having <1 *E. coli* detected in 100 ml samples. Sixty-two percent (62%) of CWP2 filter effluent samples were under 10 *E. coli*/100 ml, with 37% of samples having <1 *E. coli* detected in 100 ml samples. Eighty-five percent (85%) of household drinking water samples from control households were considered "high risk" (≥101 cfu/100 ml *E. coli*) versus 20% of samples from CWP1 intervention households (Table 4.8) and 21% of CWP2 intervention households. A summary of means of *E. coli* and turbidity counts in intervention and control household samples (both treated and untreated water) is presented in Table 4.9.

While filtrate water quality samples are useful in assessing waterborne microbial exposures, filter-treated water sample data are not necessarily indicative of filter performance, defined as a measurable reduction in microbes in water attributable to filter use. This is because untreated water may already be of high quality, or because the indicator concentration in untreated water is so high that the filter could perform admirably well and still have detectable indicator bacteria levels in samples of treated water. Performance is more meaningfully evaluated via examination of $\log_{10}$ reduction values (LRVs) (Chapter 3).

4.4.6 Diarrheal disease

4.4.6.1 Effects of filter interventions on diarrheal disease

Reduction of all diarrheal disease and dysentery by surveillance point and study group are presented in Table 4.2 (all diarrheal illness) and Table 4.3 (dysentery), with adjusted estimates of effect presented in Tables 4.4 and 4.5 (CWP1) and Tables 4.6 and 4.7 (CWP2). A clear negative association in diarrheal disease prevalence was observed in intervention (CWP1 and CWP2) households compared to control (non-filter) households, in all age groups and both sexes (Tables 4.4 and 4.5). The adjusted longitudinal prevalence proportion ratio (PPR) effect estimate for the CWP1 in all ages was 0.51 (95% CI: 0.41-0.63), corresponding to a reduction in diarrheal disease of 49%, controlling for clustering within households and within individuals over time. The adjusted prevalence proportion ratio (PPR) for the CWP2 in all ages was 0.58 (95% CI: 0.47-0.71), corresponding to a reduction in diarrheal disease of 42%, controlling for clustering within households and within individuals over time. Among children under five years of age (0-48 months at the first household visit), prevalence proportion ratios were 0.58 (95%CI: 0.41 – 0.82) for the CWP1 and 0.65 (95% CI: 0.46 – 0.93) for the CWP2. Differences between filters CWP1 and CWP2 were not statistically significant as determined by a two sample mean comparison (t) test at $\alpha = 0.05$ ($P < 0.05$) of prevalence proportion ratios.

Associations between dysentery (diarrheal disease with blood) and use of the interventions were less consistent than for all diarrheal disease (Tables 4.6 and 4.7). The adjusted longitudinal prevalence proportion ratio (PPR) effect estimate for the CWP1 in all ages was 0.39 (95% CI: 0.20-0.77), corresponding to a reduction in dysentery of 61%, controlling for clustering within households and within individuals over time. This suggests a protective effect by the filter on dysentery. However, the adjusted prevalence proportion ratio (PPR) effect estimate for the CWP2 in all ages was 0.95 (95% CI: 0.55-1.7), when controlling for clustering within households and within individuals over time. The association between dysentery and use of the CWP1 was significantly greater ($p = 0.0016$) than that between use of the CWP2 and dysentery as determined by a two sample mean comparison (t) test at $\alpha = 0.05$. Among children under five years of age (0-48 months at the first household visit), the prevalence proportion ratio for the association between CWP1 intervention use and dysentery was 0.27 (95%CI: 0.091 – 0.85), indicating a protective effect of the filter on the outcome of dysentery. The prevalence proportion ratio for the association between CWP2 intervention use and dysentery was 0.82 (95% CI: 0.35 – 1.9), a difference of effect at the margin of significance ($p = 0.0532$), as determined by a two sample mean comparison (t) test at $\alpha = 0.05$.

Overall, both filter interventions appeared to have a protective effect against risks of diarrheal disease, based on risk ratios and their 95% confidence intervals generally excluding the null (<1.0). The exceptions were for the effects of the CWP2 on risks of dysentery, for which the prevalence proportion ratios were not significantly below the null.

4.4.6.2 Diarrheal disease and water quality

Diarrheal disease (all, 7 day recall) and diarrheal disease with blood (dysentery, 7 day recall) was also examined as an outcome with water quality (*E. coli* cfu/100 ml) as the exposure variable. There was a positive association between reported diarrhea and increasing levels of *E. coli*, although this association was not strong nor did the effect increase with concentration. Estimates were adjusted for clustering within households. No other confounding variables were identified based on a 10% change-in-effect criterion for adjustment, including presence of a CWP1 or CWP2.

Results of log-risk regression are presented in Tables 4.10 and 4.11 for all diarrhea and dysentery, respectively. No difference was observed between diarrheal disease or dysentery for those having <1 *E. coli* cfu/100 ml in household drinking water and households having 1-10 *E. coli* (cfu) in 100 ml samples. Small, non-linear, but statistically significant increases in diarrheal disease were observed within strata of 11-100 *E. coli* cfu/100 ml, 101-1000 *E. coli* cfu/100 ml, and 1001+ *E. coli* cfu/100 ml.

4.4.6.3 Other associations

Measured covariates were examined for possible independent associations with diarrheal disease after controlling for the presence of the intervention (CWP1 or CWP2) and clustering within individuals over time and within households. Results are presented in Figures 4.2 - 4.5. Factors associated with decreased diarrheal disease were living in a household with greater than or the mean number of people (7+) (PPR = 0.71, 95% CI 0.60-0.84); the caregiver reporting handwashing at critical points such as after defecating, after cleaning a child, and before preparing food (PPR = 0.77, 95% CI 0.65 – 0.92); the home having a tile roof (a positive wealth indicator) (PPR = 0.69, 95% CI 0.55 – 0.86); and having an uncovered household water storage container (PPR = 0.77, 95% CI 0.68 – 0.87). Factors associated with lower reported dysentery were having electricity (a positive wealth indicator) (PPR = 0.44, 95% CI 0.26 – 0.75); having access to sanitation, either a household's own or a shared latrine (PPR = 0.59, 95% CI 0.36 – 0.99); living in a household with greater than or the mean number of people (7+) (PPR = 0.55, 95% CI 0.34-0.91); and the caregiver reporting handwashing at critical points (PPR = 0.53, 95% CI 0.32 – 0.88).

Higher diarrheal disease was reported in those under five years of age (0-48 months at the first study visit) (PPR = 2.1, 95% CI 1.8 – 2.5). Factors associated with increased dysentery were having a female interviewee for the collection of health data (PPR = 3.11, 95% CI 1.3 – 7.4); having a female caregiver (PPR = 4.1, 95% CI 1.1 – 15); being under five years of age (PPR = 2.3, 95% CI 1.4 – 3.9); and having an uncovered storage container at the time of visit (PPR = 1.9, 95% CI 1.2 – 3.1).

4.5 Discussion

4.5.1 Water quality

Water quality impacts of the intervention filters are presented in Chapter 3. In this randomized controlled field trial to evaluate the performance of two versions of the ceramic pot filter, use of a CWP1 or CWP2 was associated with a substantial improvement in drinking water quality at the household level compared to a matched control group not using filters. Both filters reduced *E. coli* in stored water (pre-treatment) by a mean 99% or 2 $\log_{10}$ (Chapter 3). A small number of samples (4.9% of CWP1 samples, 5.0% of CWP2 samples) showed a greater concentration of *E. coli* in treated water than in stored (raw) water samples, possibly due to filter contamination during improper handling or cleaning practices. The filter interventions were as effective against *E. coli* as boiling in household water management practice based on measured concentrations of *E. coli* in treated water and the differences in *E. coli* concentrations of treated and untreated household waters. These findings suggest that both boiled and filtered waters probably get recontaminated due to unsafe storage of treated water (Chapter 3). The CWP filter design does provide for safe storage in a closed container with treated water dispensed via a tap, but regular maintenance includes a cleaning step that may result in contamination of the filter element or container if cleaning involves the use of unsafe water or soiled cleaning cloths (Chapter 5).

4.5.2 Diarrheal disease impacts

4.5.2.1 Impacts of filters on diarrheal disease in study groups

Use of the filters was also associated with a reduced diarrheal disease burden, with diarrheal disease longitudinal prevalence during the study being 49% and 42% in CWP1 and CWP2 households, respectively, of that in the control (non-filter) households (all ages). A substantial reduction was also observed for bloody diarrhea through the use of a CWP1 (61%), an effect that was not observed among those using a CWP2.

Differences in health impacts between the filters were not significant for the outcome of all diarrheal disease but the CWP1 was significantly more protective of dysentery ($p = 0.0016$). One explanation may be that, after filters had been constructed and implemented, some CWP2 filters were observed to have more variable ceramic pore structure, as indicated by higher flow rates in prototype testing (data not shown). Flow rates in the CWP2 filters were 2.5 – 3.0 l/hr versus 1.5 – 2.0 l/hr in the CWP1 when fully charged (10 l). The range considered acceptable is 1.0 – 3.0 l/hr. Because the CWP2 filters used a different clay material than that normally used to make the filters (one with one part FeOOH per six parts dry clay, by weight), a loss of structural integrity may have occurred in these filters over time in use, as firing temperatures and conditions may have been suboptimal for the changed clay mixture. More work on how iron-oxide or other amendments may change the pore size, structure, and flow rate of the filter after firing is warranted to ensure maximum effectiveness of modified filters against diarrheagenic pathogens potentially present in drinking water sources. Further examination of the optimal flow conditions to maximize microbial reductions within user-acceptable flow rates would also be useful.

4.5.2.2 Diarrheal disease and water quality

There was a positive association observed between bacterial indicator levels and reported diarrheal disease, although the relationship was not strong or highly predicted by *E. coli* levels in the water. This lack of strong predictability of *E. coli* levels for diarrhea risks could be due to the inability of *E. coli* to reliably predict diarrheagenic pathogen levels in the water, changes in *E. coli* levels in water during storage or other factors we were unable to account for in this study. The lack of predictability of waterborne diarrhea risks by levels of fecal indicator bacteria such as *E. coli* has been previously reported (Jensen *et al.* 2004; Moe *et al.* 1991).

The water quality parameters used in this study are known to vary by season and diurnally, so water quality data may not represent the average drinking water quality in use by the household, especially when estimated from single samples collected no more than weekly. At best, these data represent a series of point estimates of *E. coli* in water across the community that can perhaps approximate levels of fecal contamination and waterborne pathogen concentrations across space and time. For this reason, making clear associations between water quality data based on *E. coli* levels and the outcome of diarrheal illness may be tenuous at best. Other recent studies have failed to explicitly observe this association. A meta-analysis by Gundry *et al.* (2004) concluded that there was no clear association between levels of indicator bacteria (*E. coli*, thermotolerant coliforms) and diarrhea in a systematic review of intervention trials. Similarly, Moe *et al.* (1991) found no relationship between diarrheal illness rates and good quality (<1 *E. coli*/100 ml) versus moderately contaminated water (2-100 *E. coli*/100 ml) in a field study from the Philippines. It was only when *E. coli* levels in water were above 100 cfu/100 ml that increasing concentrations were associated with increasing risks of diarrheal disease.

Possible explanations for these results are that (i), *E. coli* is not a sufficiently good indicator of waterborne diarrheal disease in the context of this study (dry season, stored household drinking water in rural Cambodia); (ii), that measured health impact data (diarrheal disease occurrence) are misleading due to a placebo effect of the filters (e.g., Hellard *et al.* 2001; Colford *et al.* 2002) and/or that drinking water may not be an important route of exposure to diarrheagenic pathogens in the population at the time of the study; (iii), that health data are biased due to recall (Boerma *et al.* 1991) or reporting issues (Thomas and Neumann 1992); or that (iv), the measured *E. coli* concentration from the time of sampling is not representative of the drinking water quality consumed by all the household members during the previous 7 days. The last point of representativeness of single water samples for 7 days of drinking water quality is particularly important, as water quality could vary greatly on a daily basis. Despite these factors tending to obscure the relationship between the fecal bacterial indicator *E. coli* and reported diarrheal disease, a positive association was observed at higher levels of *E. coli* cfu/100 ml.

4.5.2.3 Other associations

After controlling for the presence of an intervention, it was possible to identify independent associations between measured covariates and diarrheal disease outcomes in the study population. All estimates also controlled for clustering within households and within individuals over time. Wealth indicators such as having a tile roof or electricity , handwashing, and sanitation were associated with less diarrheal disease. Unexpectedly, having an uncovered water storage container at the time of the interview appeared both as a positive and negative indicator of diarrheal disease.

Having greater than the mean number of individuals in the household was associated with decreased diarrhea and decreased dysentery, possibly due to environmental health-related benefits associated with more combined wealth resources, although no clear associations between wealth, household size, and hygiene or other exposure indicators were observed. Also having a female interviewee for the collection of health data and a female caregiver in the household were associated with higher reported dysentery. These factors may be related to health data collection issues such as decreased efficiency of health data collection in large households and in greater specificity of diarrheal disease data collected from females.

4.5.3 Study limitations

The study was limited by its short duration which did not account for seasonal effects, the lack of a placebo study arm, and inherent limitations of the analytical model. Other limitations were the relatively brief periods of observation used to estimate longitudinal prevalence and issues surrounding reliable recall of diarrheal disease cases. These are briefly discussed in the following sections.

4.5.3.1 Seasonal effects

Seasonal effects on diarrheal disease prevalence or microbiological water quality were not wholly accounted for in this study due to its limited duration. The study period was unusually wet (Figure 4.1), and although data from relatively dry periods were included, there were insufficient dry-season data to present a stratified analysis by season. Water use practices, water treatment practices, diarrheal disease rates, and the presence of microbial pathogens and indicators in potential drinking water sources can vary greatly by season (Gleeson and Gray 1997). In many tropical developing countries, diarrheal disease prevalence tends to peak during or after the rainy season. The opposite may also be true in some countries where the dry season entails a shift away from the use of relatively safe rainwater to relatively unsafe surface water sources, or where water scarcity in the dry season is associated with decreased or less effective hygiene practices. Longitudinal studies that attempt to capture the protective effect of an intervention on diarrheal disease are subject to possible effect measure modification by seasonal effects, resulting in potentially very different quantitative findings over the course of a year as environmental and other conditions change.

4.5.3.2 Study design and blinding

The principal limitation of this study was the lack of any placebo (sham) filter device, which was omitted due to a combination of practical and ethical concerns. No blinded (placebo-controlled) intervention trials of household water treatment have shown significant health impacts (Clasen *et al.* 2006b), a fact that undermines the credibility of all unblinded trials. Ethical considerations are often cited for the omission of a placebo control (ibid.; Emanuel and Miller 2001), due to (i) problems with obtaining informed consent for blinded studies in marginalized, illiterate, or otherwise disadvantaged populations (Verástegui 2006; Hawkins 2006); (ii) the fact that the use of a placebo water treatment may undermine user compliance, which could influence the effectiveness of the intervention, since compliance and effectiveness may be correlated (Clasen *et al.* 2006b); and (iii) the possibility of undermining the trust that forms the basis of NGO interaction with communities.

Clause 29 of the Declaration of Helsinki (World Medical Association 1964) forbids the use of placebos when effective treatment exists (Ferriman 2001). Because implementers are often convinced that interventions are effective in reducing diarrheal disease in users, placebos for these devices may not be warranted under the Declaration of Helsinki. Amendments to clause 29 in 2002 state that a placebo may be appropriate "where a prophylactic, diagnostic or therapeutic method is being investigated for a minor condition and the patients who receive placebo will not be subject to any additional risk of serious or irreversible harm". Because water treatment interventions may stimulate a change from usual practice that may be effective at reducing disease (e.g., the treatment of drinking water by boiling or some other method, using a less contaminated source of water that might be farther away) and because these changes could carry significant risk of harm to users, the use of placebos may be unethical in trials of water treatment devices under some circumstances.

4.5.3.3 The analytical model

The modeling of potentially repeating outcomes in individuals over time yields particular challenges (Rothman and Greenland 1998). Apart from adjusting for clustering of the outcome in individuals over time, two other issues limit the methods used in this analysis.

The first is that time-dependent covariates may affect and/or be affected by the study exposure. Some covariates can influence the main exposure variable, and vice versa. Controlling for covariates may be straightforward in certain cases, since methods for effect estimation generally assume that the exposure does not affect any stratifying covariate or regressor (ibid.). But when covariates are allowed to vary over time, this is a possibility. For example, in this study, the available water source on a given day (covariate), may affect a household's decision of whether to treat the water before consumption (the exposure). Or whether or not the households have a filter (exposure) may influence the household's water storage and use practices (covariates) in the home. In these cases the covariate may be both a confounder and an intermediate, biasing estimates of effect (ibid.).

The second factor is that recurrent outcomes can confound results by affecting the exposure. Outcomes can have effects on exposure, and nowhere is this more apparent than in the study of water and hygiene related diseases transmitted fecal-orally. Current and traditional methods for the analysis of repeated measures data (such as GEE regression) do not account for the effects of outcomes on exposures, or of earlier outcomes on later ones (ibid.).

4.5.3.4 Study duration and estimation of longitudinal prevalence

More time allocated to follow-up will increase the accuracy of disease outcome estimates, but repeated household visits are often cost-prohibitive and may lead to study fatigue in participants (Schmidt *et al.* 2007). Morris *et al.* (1998) recommend a period of 72 days of observation time to reliably estimate the longitudinal diarrheal disease prevalence proportion in individuals (not groups). In this study, the baseline phase comprised 14 days of observation and the intervention phase 63, with reduced resolution from the use of binary outcome coding for the 7 day follow-up period rather than data recorded on a daily basis. So longitudinal prevalence proportions in individuals cannot be estimated using these data. Group data, however, were the focus of this study.

4.5.3.5 Diarrheal disease recall

Recall periods of greater than 48 hours may lead to underreporting of cases (Schmidt *et al.* 2007; Alam *et al.* 1989; Boerma *et al.* 1991) although 7 day recall periods are common in practice (Clasen *et al.* 2007). Logistic and resource limitations restricted the number of total household visits in this study, necessitating the use of 7 day recall to capture sufficient time at risk for participants. We assumed that an overall effect of recall time on case reporting would affect study groups equivalently, however, and so would not bias results based on differences in exposure status.

4.6 Conclusions

This study constitutes the first randomized, controlled trial of locally produced ceramic water filters for point-of-use drinking water treatment. Major findings are summarized below.

- The use of either filter resulted in a marked decrease in diarrheal disease during the study (49% reduction over the control group by use of the CWP1, 42% reduction by use of the CWP2), an effect that was observed in all age groups and both sexes after controlling for clustering within households and within individuals over time.
- The CWP1 filter was associated with a substantial reduction in dysentery (61%), an effect that was not observed with the CWP2.
- There was a positive but weak association between *E. coli* levels measured in drinking water and diarrheal disease outcomes.

Characteristic	CWP1 group n=60	CWP2 group n=60	Control group n=60
Total number of people in group	395	398	403
Mean number of individuals per household	6.58	6.63	6.72
Number (percent) female	211 (53%)	209 (53%)	211 (52%)
Number (percent) children < 5 years of age	88 (22%)	81 (20%)	80 (20%)
Number (percent) children 5-15 years of age	94 (24%)	90 (23%)	98 (24%)
Soap present in household[a]			
Yes	50 (83%)	52 (87%)	50 (83%)
No	10 (17%)	8 (13%)	10 (17%)
Reported total household income			
(USD/month)	5 (8%)	10 (17%)	5 (8%)
<$50	16 (27%)	21 (36%)	25 (42%)
$50-$99	24 (41%)	18 (31%)	18 (30%)
$100-$149	13 (22%)	7 (12%)	11 (18%)
$150-$200	1 (2%)	3 (5%)	1 (2%)
>$200			
Access to sanitation[b]			
Yes	31 (52%)	31 (52%)	33 (56%)
No	29 (48%)	29 (48%)	26 (44%)
Covered water storage container			
Yes	32 (53%)	33 (55%)	34 (57%)
No	28 (47%)	27 (45%)	26 (43%)
Wash hands with soap?[d]			
Yes	32 (53%)	32 (53%)	35 (58%)
No	28 (47%)	28 (47%)	25 (42%)
Primary drinking water sources: dry season[e]			
Surface water	37 (62%)	31 (52%)	33 (55%)
Groundwater			
Deep well (≥10m)	27 (45%)	30 (50%)	29 (48%)
Shallow well	0 (0%)	0 (0%)	0 (0%)
Rainwater	2 (3%)	0 (0%)	1 (2%)
Primary drinking water sources: wet season[e]			
Surface water	33 (55%)	31 (52%)	27 (45%)
Groundwater			
Deep well (≥10m)	26 (43%)	28 (47%)	29 (48%)
Shallow well	1 (2%)	0 (0%)	0 (0%)
Rainwater	44 (73%)	39 (65%)	44 (73%)
Observed method of drawing water[f]			
Use hands	36 (60%)	20 (33%)	27 (45%)
Pour or tap	24 (40%)	40 (67%)	23 (38%)
Formal education level of primary caregiver[g]			
None	13 (22%)	10 (17%)	15 (25%)
Some or all primary school	38 (63%)	28 (47%)	27 (45%)
Some or all secondary school	6 (10%)	22 (37%)	17 (28%)
More than secondary (e.g., vocational)	3 (5%)	0 (0%)	1 (2%)

a. Respondents were asked to demonstrate that soap was present in the household.
b. Shared or own latrine (any type).
d. Users who responded that they did wash hands "always" with soap at critical points such as after defecating.
e. Multiple answers possible. Most of the study took place in the wet season.
f. Respondents were asked to demonstrate their usual method of gathering water from the storage container.
g. Usually an adult female who is responsible for child care.

Table 4.1. Characteristics of study groups.

Surveillance Point	*Group*	*Longitudinal prevalence proportion*	*Prevalence proportion ratio*	*Cases*	*Person-days at risk*[a]	*Incidence rate*	*Incidence rate ratio (95% CI)*	*Adjusted PPR (95%CI) by GEE*[b]
1	All (baseline)	0.18		202	7094	0.029		
2	All (baseline)	0.18		208	7482	0.028		
3	Control	0.20		80	2497	0.032		
	CWP1	0.12	0.60	45	2588	0.017	0.54 (0.37-0.79)	0.57 (0.39-0.81)
	CWP2	0.094	0.47	36	2587	0.014	0.43 (0.28-0.65)	0.68 (0.56-0.82)
4	Control	0.18		69	2537	0.027		
	CWP1	0.094	0.52	37	2633	0.014	0.52 (0.34-0.78)	0.54 (0.36-0.80)
	CWP2	0.10	0.56	40	2561	0.016	0.57 (0.38-0.86)	0.77 (0.63-0.94)
5	Control	0.13		52	2595	0.020		
	CWP1	0.08	0.62	31	2651	0.012	0.58 (0.36-0.93)	0.60 (0.38-0.93)
	CWP2	0.11	0.85	42	2555	0.016	0.82 (0.53-1.3)	0.91 (0.74-1.1)
6	Control	0.13		49	2576	0.019		
	CWP1	0.07	0.54	26	2617	0.0099	0.52 (0.31-0.86)	0.54 (0.33-0.86)
	CWP2	0.090	0.69	35	2618	0.013	0.70 (0.44-1.1)	0.85 (0.68-1.1)
7	Control	0.10		41	2628	0.016		
	CWP1	0.075	0.75	29	2608	0.011	0.71 (0.43-1.2)	0.72 (0.45-1.2)
	CWP2	0.070	0.70	27	2614	0.010	0.66 (0.39-1.1)	0.82 (0.64-1.1)
8	Control	0.14		52	2427	0.021		
	CWP1	0.060	0.43	22	2517	0.0087	0.41 (0.24-0.68)	0.42 (0.26-0.70)
	CWP2	0.064	0.46	24	2553	0.0094	0.44 (0.26-0.72)	0.67 (0.53-0.86)
9	Control	0.17		63	2380	0.027		
	CWP1	0.054	0.32	20	2530	0.0079	0.30 (0.17-0.50)	0.31 (0.19-0.52)
	CWP2	0.070	0.41	26	2540	0.010	0.39 (0.23-0.62)	0.64 (0.51-0.80)
10	Control	0.13		47	2372	0.020		
	CWP1	0.060	0.46	22	2503	0.0088	0.44 (0.25-0.75)	0.46 (0.28-0.76)
	CWP2	0.093	0.72	35	2534	0.014	0.70 (0.44-1.1)	0.84 (0.68-1.1)
11	Control	0.12		45	2406	0.019		
	CWP1	0.053	0.44	20	2572	0.0078	0.42 (0.23-0.72)	0.43 (0.25-0.73)
	CWP2	0.11	0.92	38	2385	0.016	0.85 (0.54-1.3)	0.93 (0.75-1.2)

a. Cases were assigned a mean duration of 3 days; thus cases received 4 days of at-risk time during each seven day observation period.

b. Prevalence proportion ratio estimated via Poisson extension of Generalized Estimating Equations (GEE), adjusted for clustering within households.

Table 4.2. Summary of longitudinal data for diarrheal disease (all) by biweekly surveillance point.

Surveillance Point	*Group*	*Longitudinal prevalence proportion*	*Prevalence proportion ratio*	*Cases*	*Person-days at risk*[a]	*Incidence rate*	*Incidence rate ratio (95% CI)*	*Adjusted PPR (95%CI) by GEE*[b]
1	All (baseline)	0.018		20	7574	0.0026		
2	All (baseline)	0.016		18	7980	0.0023		
3	Control	0.013		5	2702	0.0019		
	CWP1	0.0051	0.39	2	2709	0.00074	0.40 (0.038-2.4)	0.40 (0.078-2.1)
	CWP2	0.013	1.0	5	2660	0.0019	1.0 (0.23-4.4)	1.0 (0.54-1.9)
4	Control	0.0077		3	2723	0.0011		
	CWP1	0.0026	0.34	1	2737	0.00037	0.33 (0.010-4.1)	0.33 (0.035-3.2)
	CWP2	0.010	1.3	4	2653	0.0015	1.4 (0.23-9.3)	1.2 (0.55-2.5)
5	Control	0.0076		3	2730	0.0011		
	CWP1	0.0051	0.67	2	2730	0.00073	0.67 (0.06-5.8)	0.67 (0.11-4.0)
	CWP2	0.018	2.4	7	2632	0.0027	2.4 (0.55-15)	1.6 (0.79-3.04)
6	Control	0.010		4	2695	0.0015		
	CWP1	0.0052	0.52	2	2681	0.00075	0.50 (0.056-3.5)	0.51 (0.093-2.8)
	CWP2	0.013	1.3	5	2688	0.00189	1.3 (0.27-6.3)	1.1 (0.58-2.2)
7	Control	0.0051		2	2737	0.00073		
	CWP1	0.0026	0.51	1	2688	0.00037	0.51 (0.010-9.8)	0.51 (0.046-5.6)
	CWP2	0.0078	1.5	3	2674	0.0011	1.5 (0.18-18)	1.2 (0.51-3.0)
8	Control	0.024		9	2520	0.0036		
	CWP1	0.0081	0.34	3	2562	0.0012	0.33 (0.057-1.3)	0.33 (0.090-1.2)
	CWP2	0.0027	0.11	1	2618	0.00038	0.11 (0.0020-0.77)	0.33 (0.12-0.93)
9	Control	0.0082		3	2548	0.0012		
	CWP1	0.0081	0.99	3	2562	0.0012	0.99 (0.13-7.4)	0.99 (0.20-4.9)
	CWP2	0.0053	0.65	2	2611	0.00077	0.65 (0.054-5.7)	0.81 (0.33-2.0)
10	Control	0.017		6	2471	0.0024		
	CWP1	0.0027	0.16	1	2562	0.00039	0.16 (0.0030-1.3)	0.16 (0.020-1.4)
	CWP2	0.013	0.76	5	2604	0.0019	0.79 (0.19-3.1)	0.89 (0.49-1.6)
11	Control	0.019		7	2492	0.0028		
	CWP1	0.0027	0.14	1	2625	0.00038	0.14 (0.0030-1.1)	0.14 (0.017-1.1)
	CWP2	0.017	0.89	6	2457	0.0024	0.87 (0.24-3.0)	0.93 (0.54-1.6)

a. Cases were assigned a mean duration of 7 days; thus cases received 0 days of at-risk time during each seven day observation period.

b. Prevalence proportion ratio estimated via Poisson extension of Generalized Estimating Equations (GEE), adjusted for clustering within households.

Table 4.3. Summary of longitudinal data for dysentery (diarrheal disease with blood) by biweekly surveillance point.

	Mean diarrheal disease prevalence proportion over 18 week intervention period[a]		*Incidence rate ratio (IRR)*[b] *(95% CI*[c]*)*	*Prevalence proportion ratio (PPR)*[d] *(95% CI)*
	Control	Intervention (CWP1)		
All persons	0.15	0.074	0.57 (0.50-0.65)	0.51 (0.41-0.63)
Age[e]				
<5 years	0.23	0.14	0.67 (0.54-0.83)	0.58 (0.41-0.82)
5-15 years	0.13	0.079	0.63 (0.48-0.83)	0.62 (0.43-0.90)
≥16 years	0.12	0.045	0.44 (0.35-0.54)	0.37 (0.26-0.52)
Sex				
Male	0.12	0.076	0.65 (0.53-0.79)	0.61 (0.44-0.83)
Female	0.17	0.072	0.52 (0.43-0.61)	0.44 (0.33-0.58)

a. Nine sampling rounds, June-October 2006. Figures represent the proportion of individuals reporting diarrhea in the previous 7 days.
b. Assumed case duration of three days; individuals reporting cases in the previous seven days were assigned four days of person time at risk.
c. 95% confidence interval.
d. This PPR was computed via log-linear Poisson extension of generalized estimating equations (GEE), adjusting for clustering of the outcome within households and within individuals over time.
e. Age in years at the time of the first household visit.

Table 4.4. Diarrheal disease prevalence proportions and filter effect estimates (CWP1) by age and sex of individuals.

	Mean diarrheal disease prevalence proportion over 18 week intervention period[a]		*Incidence rate ratio (IRR)*[b] *(95% CI*[c]*)*	*Prevalence proportion ratio (PPR)*[d] *(95% CI)*
	Control	Intervention (CWP2)		
All persons	0.15	0.090	0.69 (0.61-0.78)	0.58 (0.47-0.71)
Age[e]				
<5 years	0.24	0.19	0.75 (0.61-0.93)	0.65 (0.46-0.93)
5-15 years	0.14	0.078	0.54 (0.40-0.71)	0.48 (0.31-0.75)
≥16 years	0.13	0.091	0.70 (0.59-0.84)	0.57 (0.42-0.76)
Sex				
Male	0.12	0.081	0.74 (0.61-0.89)	0.60 (0.43-0.83)
Female	0.17	0.096	0.65 (0.55-0.76)	0.57 (0.44-0.75)

a. Nine sampling rounds, June-October 2006. Figures represent the proportion of individuals reporting diarrhea in the previous 7 days.

b. Assumed case duration of three days; individuals reporting cases in the previous seven days were assigned four days of person time at risk.

c. 95% confidence interval.

d. This PPR was computed via log-linear Poisson extension of generalized estimating equations (GEE), adjusting for clustering of the outcome within households and within individuals over time.

e. Age in years at the time of the first household visit.

Table 4.5. Diarrheal disease prevalence proportions and filter effect estimates (CWP2) by age and sex of individuals.

	Mean bloody diarrhea prevalence proportion over 18 week intervention period[a]		*Incidence rate ratio (IRR)*[b] *(95% CI*[c]*)*	*Prevalence proportion ratio (PPR)*[d] *(95% CI)*
	Control	Intervention (CWP1)		
All persons	0.012	0.0047	0.43 (0.26-0.69)	0.39 (0.20-0.77)
Age[e]				
<5 years	0.025	0.0079	0.46 (0.21-0.96)	0.27 (0.091-0.85)
5-15 years	0.0082	0.0061	0.69 (0.20-2.2)	0.52 (0.10-2.7)
≥16 years	0.0095	0.0027	0.29 (0.12-0.66)	0.29 (0.11-0.80)
Sex				
Male	0.0074	0.0044	0.81 (0.41-1.6)	0.49 (0.17-1.5)
Female	0.017	0.0049	0.37 (0.19-0.69)	0.31 (0.13-0.73)

a. Nine sampling rounds, June-October 2006. Figures represent the proportion of individuals reporting diarrhea in the previous 7 days.

b Assumed case duration of seven days; individuals reporting cases in the previous seven days were assigned zero days of person time at risk.

c. 95% confidence interval.

d. This PPR was computed via log-linear Poisson extension of generalized estimating equations (GEE), adjusting for clustering of the outcome within households and within individuals over time.

e. Age in years at the time of the first household visit.

Table 4.6. Dysentery (diarrhea with blood) prevalence proportions and filter effect estimates (CWP1) by age and sex of individuals.

	Mean bloody diarrhea prevalence proportion over 18 week intervention period[a]		*Incidence rate ratio (IRR)*[b] *(95% CI*[c]*)*	*Prevalence proportion ratio (PPR)*[d] *(95% CI)*
	Control	Intervention (CWP2)		
All persons	0.012	0.011	0.80 (0.54-1.2)	0.95 (0.55-1.7)
Age[e]				
<5 years	0.025	0.017	0.71 (0.36-1.4)	0.82 (0.35-1.9)
5-15 years	0.0082	0.012	1.3 (0.50-3.6)	1.5 (0.40-5.5)
≥16 years	0.0096	0.0083	0.70 (0.38-1.3)	0.87 (0.37-2.0)
Sex				
Male	0.0074	0.0098	1.0 (0.55-2.0)	1.2 (0.50-2.9)
Female	0.017	0.012	0.67 (0.39-1.1)	0.68 (0.32-1.4)

a. Nine sampling rounds, June-October 2006. Figures represent the proportion of individuals reporting diarrhea in the previous 7 days.
b. Assumed case duration of seven days; individuals reporting cases in the previous seven days were assigned zero days of person time at risk.
c. 95% confidence interval.
d. This PPR was computed via log-linear Poisson extension of generalized estimating equations (GEE), adjusting for clustering of the outcome within households and within individuals over time.
e. Age in years at the time of the first household visit.

Table 4.7. Dysentery (diarrhea with blood) prevalence proportions and filter effect estimates (CWP2) by age and sex of individuals.

	Number (percentage[a]) of all samples by E. coli *concentration of household drinking water[b]*					
	0 (cfu/100 ml)	1-10 (cfu/100 ml)	11-100 (cfu/100 ml)	101-1000 (cfu/100 ml)	1,001+ (cfu/100 ml)	Total samples[c]
Control households	6 (1%)	20 (3%)	65 (11%)	294 (49%)	221 (36%)	606
CWP1	243 (40%)	116 (19%)	121 (20%)	87 (14%)	37 (6%)	604
CWP2	228 (37%)	152(25%)	102 (17%)	79 (13%)	49 (8%)	610

a. Percentages within strata may not add up to 100% due to rounding.
b. Samples were filter effluent in intervention households, stored household drinking water for control households (including samples from treatment by boiling). Households were asked to provide a sample of the water that the family was drinking at the time of visit.
c. Incomplete data for 54 (8%) control households, 56 (8%) for CWP1 households, and 50 (8%) for CWP2 households.

Table 4.8. Measured levels of *E. coli* (cfu/100 ml) in household drinking water by study group.

	Water quality data[a]*, means (95% CI*[b]*) (untreated water)*		*Water quality data*[a]*, means (95% CI*[b]*) (treated water)*	
	E.coli/100 ml	Turbidity (NTU)	*E.coli*/100 ml	Turbidity (NTU)
Control				
Arithmetic	3000 (2500-3500)	10.8 (10.1-11.5)	120 (55-190)	8.18 (6.50-9.87)
Geometric	600 (570-640)	5.47 (5.32-5.63)	22 (15-33)	5.08 (4.53-5.70)
CWP1				
Arithmetic	3500 (3000-4000)	7.54 (7.12-7.96)	110 (46-170)	3.08 (2.70-3.46)
Geometric	520 (490-550)	4.81 (4.70-4.92)	17 (14-22)	2.41 (2.28-2.54)
CWP2				
Arithmetic	1800 (1500-2000)	8.71 (8.25-9.16)	110 (60-170)	3.08 (2.32-3.83)
Geometric	420 (400-450)	5.18 (5.05-5.31)	15 (12-18)	2.32 (2.20-2.44)

a. Data from intervention households, raw (untreated) water and filtered (treated water) samples from 9 sampling rounds.
b. 95% confidence intervals.

Table 4.9. Mean *E. coli* counts (cfu/100 ml) and turbidity averages for samples taken in intervention households (untreated and treated water).

E. coli*/100 ml in household drinking water*[a]	*Stratum-specific risk estimate, all diarrheal disease*[b]	*Prevalence proportion ratio (PPR)*[c]	*95% CI*
<1	0.084	1.0 (referent)	
1-10	0.082	0.98	0.81-1.2
11-100	0.11	1.2	1.1-1.3
101-1000	0.15	1.2	1.2-1.3
1001+	0.15	1.2	1.1-1.2

a. Samples were filter effluent in intervention households, stored household drinking water for control households. Households were asked to provide a sample of the water that the family was drinking at the time of visit.
b. Prevalence proportion of those reporting diarrheal diseases (all) within the previous 7 days. Diarrhea was defined as 3 or more loose or watery stools within 24 hours.
c. Computed by log-linear Poisson extension of generalized estimating equations (GEE), adjusted for clustering within households. No other confounding variables were identified based on a 10% *a priori* change-in-estimate criterion, including presence of the intervention (CWP1 or CWP2).

Table 4.10. Stratum-specific risk estimates for levels of *E. coli* in household drinking water samples, diarrheal disease in last 7 days.

E. coli*/100 ml in household drinking water*[a]	*Stratum-specific risk estimate, bloody diarrhea*[b]	*Prevalence proportion ratio (PPR)*[c]	*95% CI*
<1	0.0075	1.0 (referent)	.
1-10	0.0056	0.75	0.36-1.6
11-100	0.014	1.4	1.0-1.8
101-1000	0.013	1.2	1.0-1.4
1001+	0.015	1.2	1.0-1.3

a. Samples were filter effluent in intervention households, stored household drinking water for control households. Households were asked to provide a sample of the water that the family was drinking at the time of visit.
b. Prevalence proportion of those reporting diarrhea (with blood present in the stool) within the previous 7 days. Diarrhea was defined as 3 or more loose or watery stools within 24 hours.
c. Computed by log-linear Poisson extension of generalized estimating equations (GEE), adjusted for clustering within households. No other confounding variables were identified based on a 10% *a priori* change-in-estimate criterion, including presence of the intervention (CWP1 or CWP2).

Table 4.11. Stratum-specific risk estimates for levels of *E. coli* in household drinking water samples, diarrheal disease with blood (dysentery) in last 7 days.

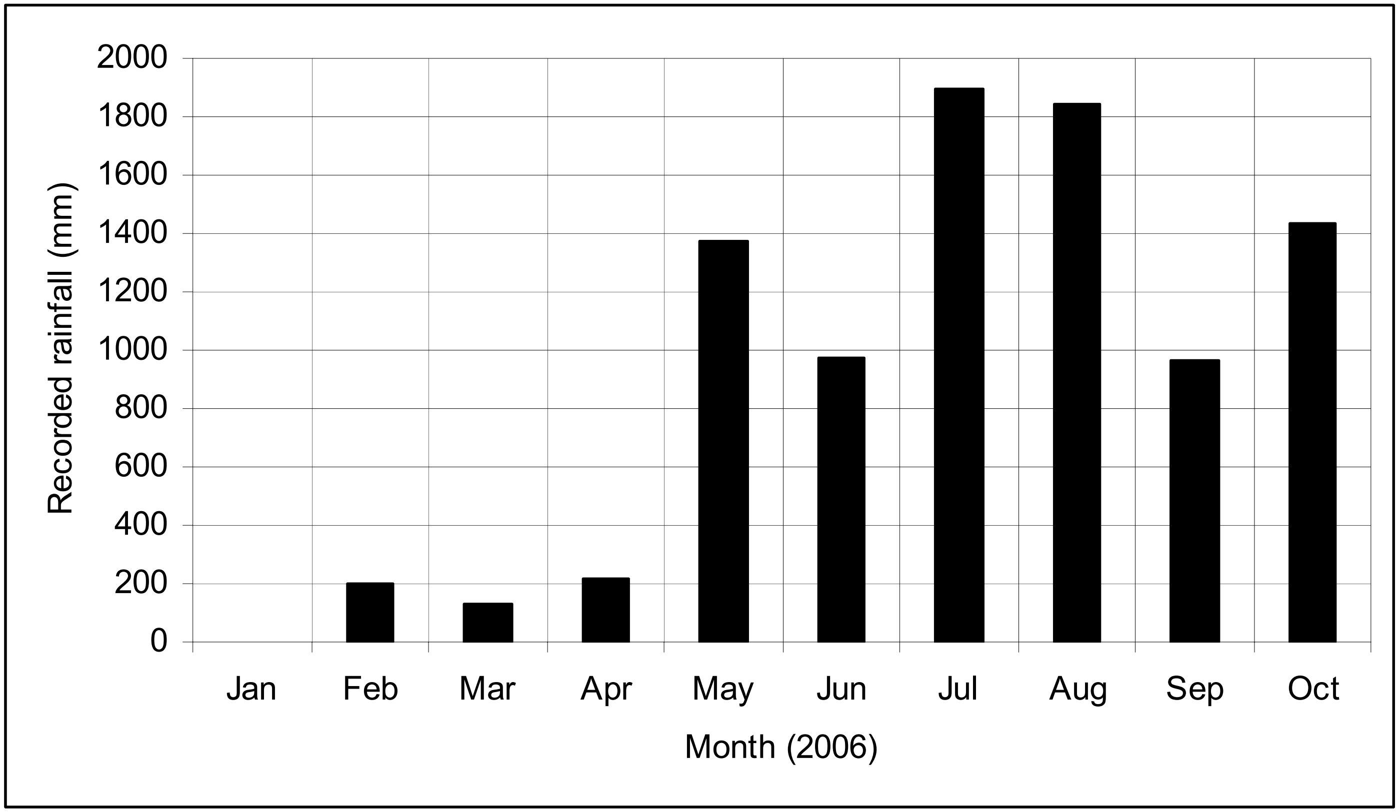

Figure 4.1. Rainfall (mm) per month in 2006, from weather station at Resource Development International (RDI), located approximately 10km from Prek Thmey village. The rainiest months are typically October and November, but May, June, July and August were especially rainy in 2006. Values are extrapolated from available monthly data, which range from 31% to 100% complete.

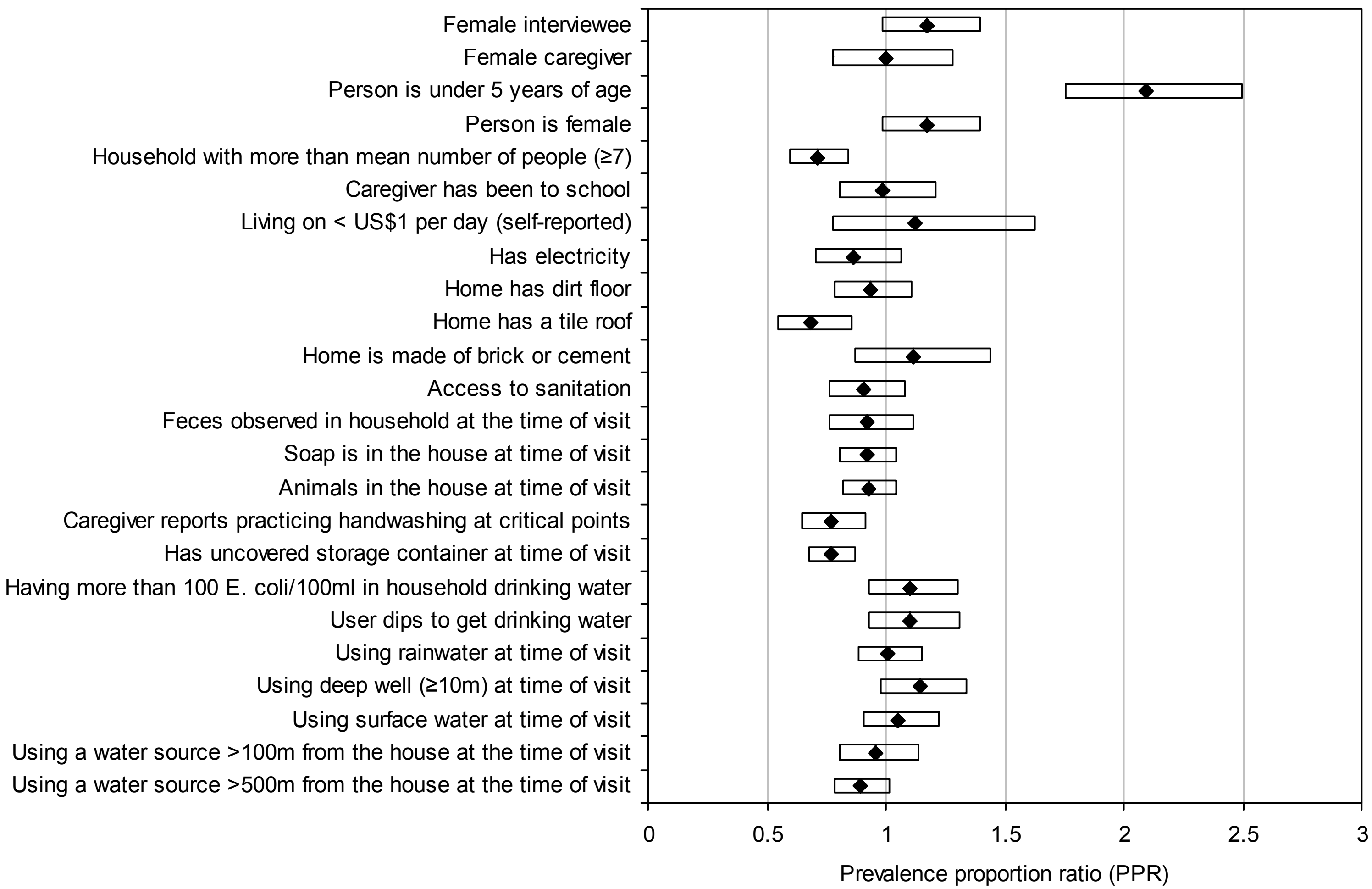

Figure 4.2. Association of measured covariates with diarrheal disease in all individuals, adjusted for presence of the intervention (CWP1 or CWP2) and for clustering within households and in individuals over time. Points are arithmetic mean prevalence proportion ratios and bars represent 95% confidence intervals.

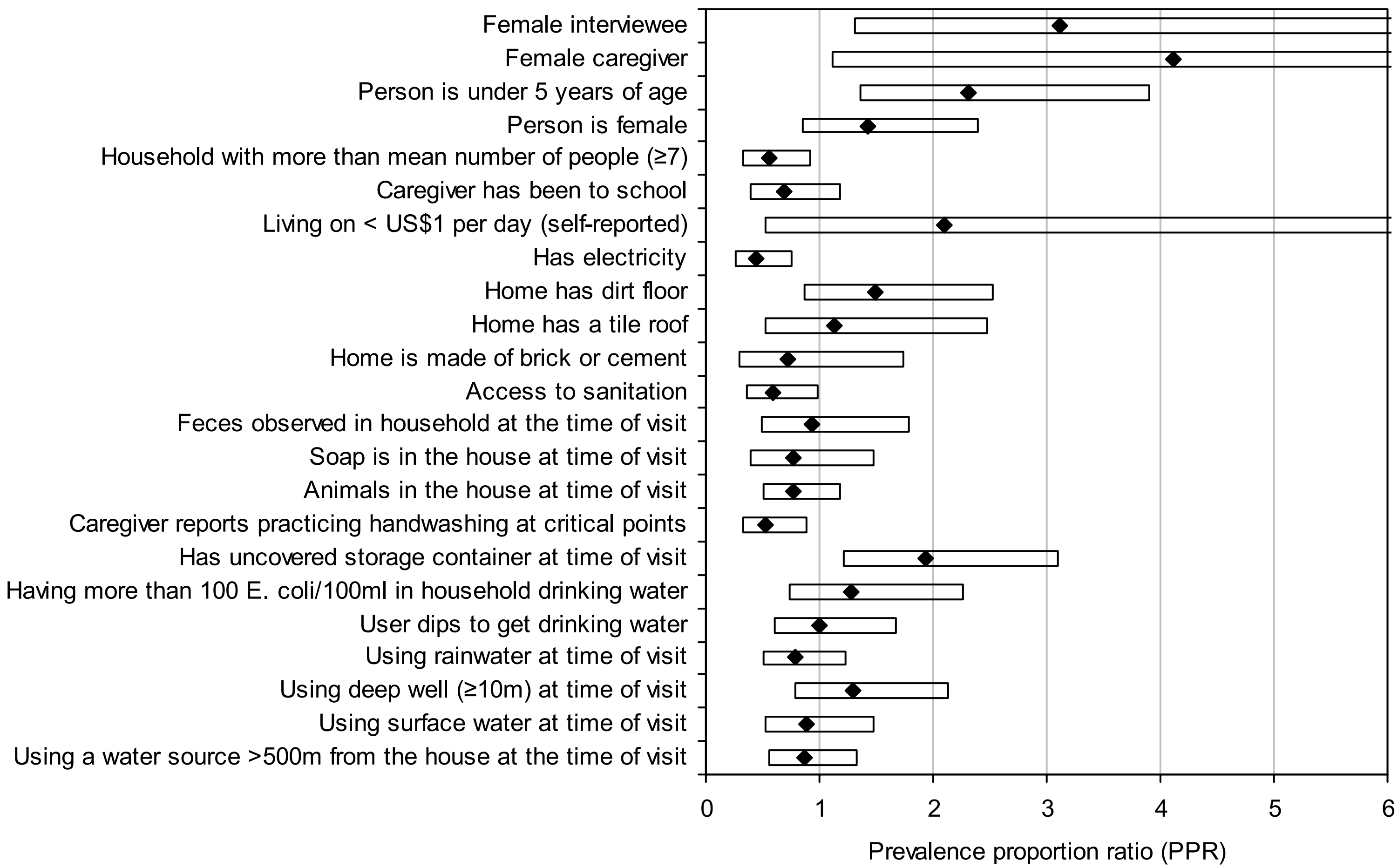

Figure 4.3. Association of measured covariates with dysentery in all individuals, adjusted for presence of the intervention (CWP1 or CWP2) and for clustering within households and in individuals over time. Points are arithmetic mean prevalence proportion ratios and bars represent 95% confidence intervals.

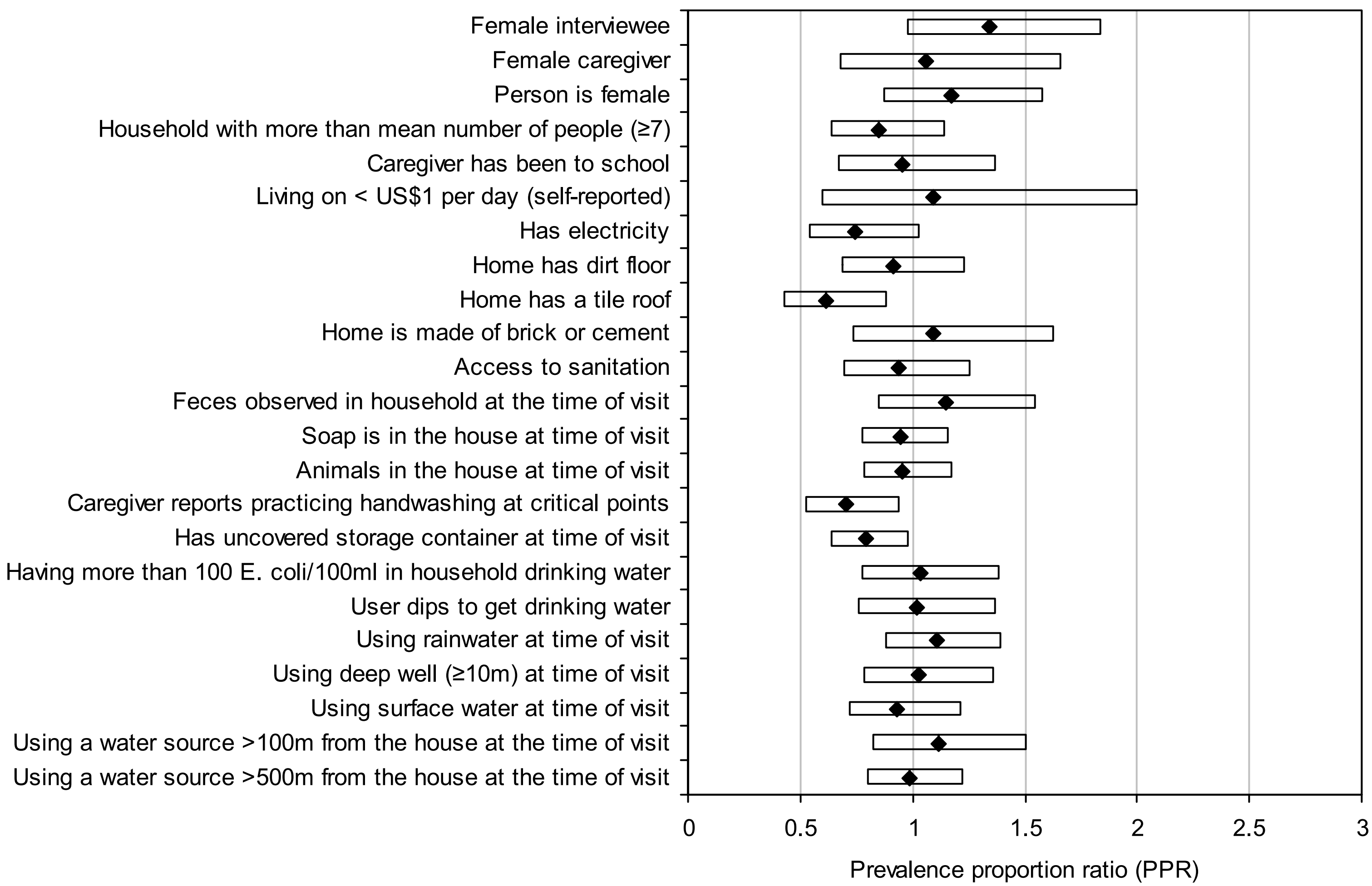

Figure 4.4. Association of measured covariates with diarrheal disease in children under five years of age, adjusted for presence of the intervention (CWP1 or CWP2) and for clustering within households and in individuals over time. Points are arithmetic mean prevalence proportion ratios and bars represent 95% confidence intervals.

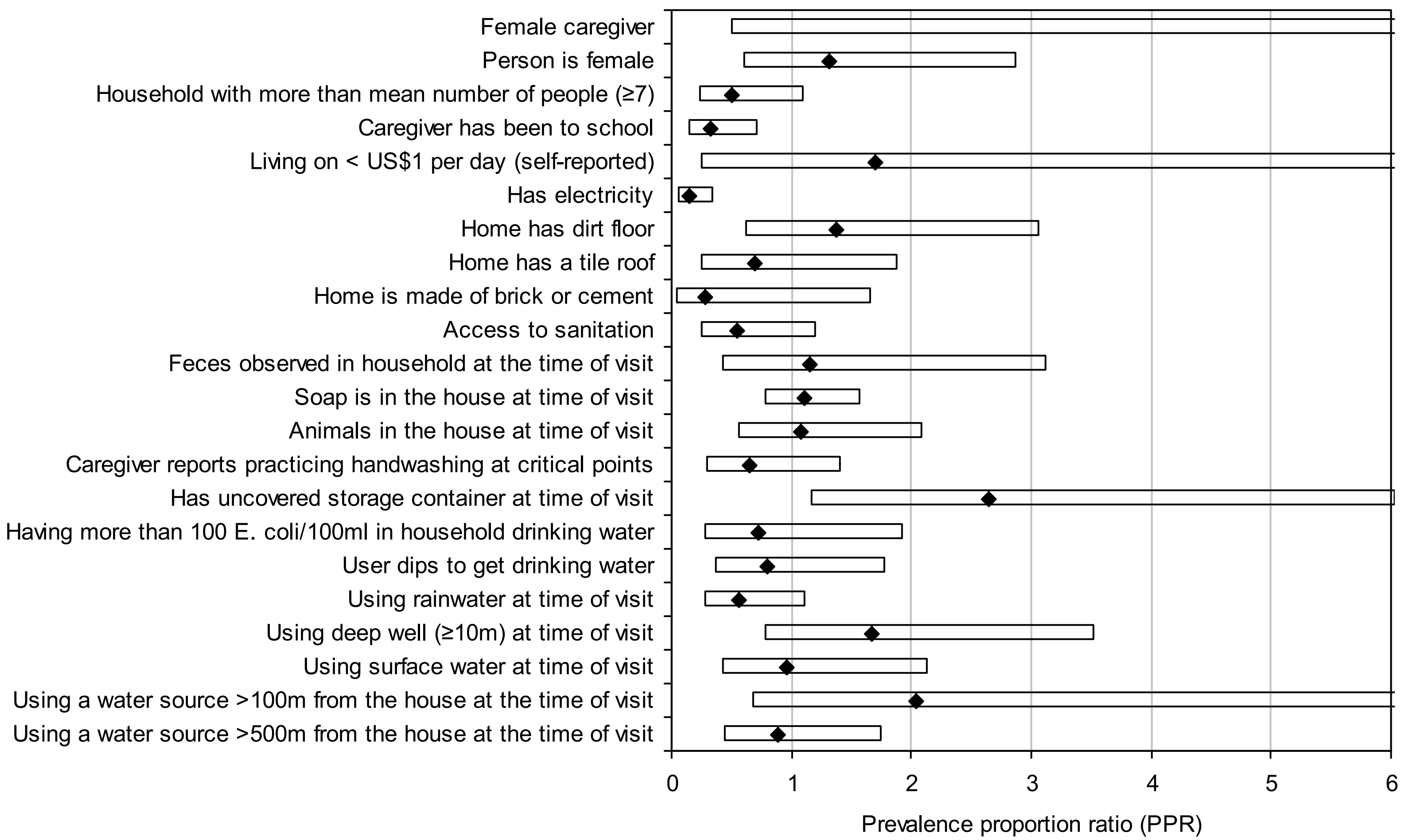

Figure 4.5. Association of measured covariates with dysentery in children under the age of five, adjusted for presence of the intervention (CWP1 or CWP2) and for clustering within households and in individuals over time. Points are arithmetic mean prevalence proportion ratios and bars represent 95% confidence intervals.

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CHAPTER 5: CERAMIC FILTERS FOR POINT-OF-USE DRINKING WATER TREATMENT IN RURAL CAMBODIA: INDEPENDENT APPRAISAL OF INTERVENTIONS FROM 2002-2005

Abstract

This study is an independent follow-up assessment of two large-scale implementations of the household-scale ceramic drinking water purifier (CWP) conducted by two NGOs over a period of forty-four months (2002-2005) in rural Cambodia. Approximately 1000 household filters were introduced by Resources Development International (RDI) in Kandal Province from December 2003 and 1000+ filters by International Development Enterprises (IDE) in Kampong Chhnang and Pursat provinces from July 2002. This study assesses the water quality and health impacts of the CWP interventions to date.

The study was carried out in three parts: (i) a cross-sectional study of households that originally received filters to determine uptake and use proportions, as well as factors associated with continued use of the technology; (ii) a water quality assessment in 80 households successfully using the filters (from part 1) to determine the microbiological effectiveness of the filters in treating household water, focusing on both treated and untreated water; and (iii) a longitudinal health study comparing diarrheal disease prevalence in 80 households using the filters successfully to 80 control households (without filters). Control households were matched by water source, socio-economic

criteria, demographic data, and physical proximity. Water quality data were collected for control households as well, including stored, boiled water samples, if available.

Findings of this study included: (i) the rate of filter disuse was approximately 2% per month after implementation, due largely to breakages; (ii) controlling for time since implementation, continued filter use over time was most closely positively associated with related water, sanitation, and hygiene practices in the home, cash investment in the technology by the household, and use of surface water as a primary drinking water source; (iii) the filters reduced *E. coli*/100 ml counts by a mean 98% in treated versus untreated household water; (iv) microbiological effectiveness of the filters was not observed to be closely related to time in use; (v) the filters can be highly effective in reducing microbial indicator organisms but may be subject to recontamination, probably during "cleaning" with soiled cloths; and (vi) the filters were associated with an estimated 46% reduction in diarrhea in filter users versus non users (prevalence proportion ratio: 0.54, 95% CI 0.41-0.71).

5.1 Introduction

5.1.1 Water quality and diarrheal diseases in Cambodia

For the estimated 66% of Cambodians without access to improved drinking water sources (NIS 2004) and the potentially much greater percentage without consistent access to microbiologically safe water at the point of use, household-based water treatment can play a critical role in protecting users from waterborne disease. Surface water in Cambodia is plentiful but often of very poor quality, due in part to inadequate or nonexistent sanitation in both rural and urban areas. Only 16% of Cambodians have access to adequate sanitation facilities (ibid.). Some groundwater sources in the country are also known to contain high levels of naturally occurring arsenic and other chemical contaminants (Feldman *et al.* 2007; Polya *et al.* 2005). Arsenic in the groundwater is an especially urgent problem in parts of the lower Mekong delta region where there is a high population density. The first cases of arsenicosis in Cambodia were reported in August 2006, in Kandal province (Saray 2006). Surface water and shallow groundwater (often of poor microbiological and aesthetic quality) and rain water catchment sources (susceptible to contamination during storage) are the principal alternatives to arsenic-contaminated deep wells.

According to Cambodian national health statistics for the year 2000, the prevalence of childhood diarrhea (children aged 0-60 months) is 18.9%, based on a 14-day recall period. Prevalence in and around Phnom Penh is 24.4% (NIS 2000). National data on diarrhea for older children and adults have not been collected, as children under 5 years represent the most at-risk group and therefore have been the focus of surveys. There were an estimated 309,933 reported cases of diarrhea (including dysentery) in Cambodia in 2000, out of a population of approximately 13 million (WHO 2004). Diarrheal disease morbidity and mortality is often underreported, however.

5.1.2 Study overview

An emerging point-of-use treatment technology is the ceramic water purifier (CWP), a household-scale, porous ceramic filter. Commercially produced ceramic candle filters have been found to not only improve water quality at the point of use but also reduce household diarrheal disease (Clasen *et al.* 2004; Clasen *et al.* 2006a). The ceramic filter intervention evaluated in this study, however, has not been well characterized for its performance in the field to reduce diarrheal diseases. Its effectiveness over long periods of regular use in the field has also not been well studied previously. Knowledge of these factors is critical and prerequisite to successful scale-up and further investment in the technology.

This study is an independent follow-up assessment of two large-scale implementations of the household-scale ceramic drinking water purifier (CWP) after 0-44 months in use. Approximately 1000 household filters were introduced by Resources Development International (RDI) in Kandal Province beginning in December 2003 and 1000+ filters by International Development Enterprises (IDE) in Kampong Chhnang and Pursat provinces beginning in July 2002. The American Red Cross, CIDA, AusAID, UNICEF, and the World Bank Development Marketplace Programme have supplied support to these two NGOs for various parts of the production and distribution cycle of the filters.

Key research objectives identified by stakeholders were to: (i), evaluate the extent that filters improve microbiological quality of drinking water at the point of use; (ii), evaluate the extent to which filter protect users from diarrheal disease; (iii), determine whether and how filter effectiveness against microbes and/or diarrheal disease changes over time; (iv), determine how long filters are in use in households; and (v), identify factors associated with long-term use and factors associated with discontinuation of use to inform future and current implementation efforts.

To meet these objectives, the following were measured: (i), the continued use of the filters over time as the proportion of initial filters still in use since introduction, and the identification of factors potentially associated with filter uptake and long term use; (ii), the microbiological effectiveness *in situ* of the filters still being used, as determined by the $\log_{10}$ reduction of the indicator organism *E. coli*; and (iii), the health impacts of the filters as determined by a prospective cohort study using data on diarrheal disease prevalence and incidence estimates among filter users versus non-users. Survey data intended to elucidate factors influencing implementation success and the challenges facing the long-term sustainability of this intervention in Cambodia were also collected.

5.2 Purpose and objectives

The purpose of this study was to assess continued use, continued microbiological effectiveness, and associated health impacts of the CWP filter after up to 4 years of use (0 – 44 months) in households in rural Cambodia. The study hypothesis was that the CWP as currently produced would continue to be used effectively in households in rural Cambodia beyond initial intervention programs, and that use of the intervention would be associated with improved household water quality and a reduction in diarrheal disease among users against a matched control group of households that never had filters.

The specific objectives of this study were to:

- assess uptake of the filters as implemented over 44 months by independently verifying use,
- identify factors related to continued use or disuse since implementation,
- assess microbiological effectiveness of filters as implemented by measuring *E. coli* in stored versus treated household water,

- determine whether an association exists between microbiological performance of filters and time in use,
- assess health impacts by measuring diarrheal disease outcomes in households with access to filters versus a matched control group, and
- examine the association between household water quality and diarrheal disease between the filter and control groups.

5.3 Methods and materials

5.3.1 Overview of methods

The study was carried out in three parts: (i), a cross-sectional study of households that originally received filters to determine uptake and use proportions, as well as factors associated with continued use of the technology; (ii), a water quality assessment in 80 households successfully using the filters (from part 1) to determine the microbiological effectiveness of the filters in treating household water, focusing on both treated and untreated water; and (iii), a longitudinal health study comparing diarrheal disease prevalence in 80 households using the filters successfully to 80 control households (without filters). Control households were matched by water source, socio-economic criteria, demographic data, and physical proximity. Water quality data were collected for control households as well, including stored, boiled water samples, if available.

5.3.2 The intervention

Ceramic filtration is the use of porous ceramic (fired clay) to filter microbes or other contaminants from drinking water. Pore size can be made small enough to remove virtually all bacteria and protozoa by size exclusion, down to 0.2μm, in the range referred to as microfiltration. Small-scale ceramic filtration has a long history, having been used in various forms since antiquity (Sobsey 2002).

The ceramic water purifier (CWP) is a flower pot shaped (i.e., "pot-style") ceramic filter. Porosity in the ceramic (< 1μm and larger) is created by mixing burnout material into the unfired clay, which is typically very fine sawdust, ground rice husks, or some other combustible material that disintegrates during the firing process to leave behind pore space. Water passes through the porous ceramic filter element (capacity approximately 10 l) at 1-3 l/hr into the receiving container (10-20 l), where it is dispensed via a tap to prevent post-filtration contamination of the product water through dipping or other contact with soiled hands or vessels. Filters are often treated with a silver compound or other agent to inhibit microbial growth in the filter and possibly to enhance microbiological effectiveness. Porous ceramic filters vary widely in design, effectiveness, and cost. The model for the CWP is the ICAITI filter developed in Latin America in the early 1980s (AFA Guatemala 1995), promoted widely by the NGO Potters for Peace.

The CWPs under study here are from two NGO manufacturers in Cambodia, International Development Enterprises (IDE) and Resource Development International (RDI). Their designs, production methods, silver treatment methods, and quality control steps are distinct but similar. This study was not intended to sort out the better method of production or effectiveness between the technologies themselves. They were assumed similar enough to be comparable under field conditions.

5.3.3 Cross-sectional study

5.3.3.1 Overview

In order to evaluate the successful adoption of the filters, 600 households were randomly selected from the original 2000 households that received filters in three provinces. Of these, 506 could be located and consented to participate, and so were included in the cross-sectional assessment. After obtaining informed consent from the head of household (and primary caregiver for the children, if a different person), the data collection team first determined whether the filter was in current use. Criteria for 'current use' were that the filter: (i), was in good working order (filter element, tap, and receptacle intact and apparently functional); (ii), that it contained water or was damp from recent use; and (iii), one or more household members reported daily use for the production of drinking water. Since filters typically take 3 or more days to dry completely, filters that were dry were not considered in current use. Each household was scored on filter use and a questionnaire was administered to the adult primary caregiver for the household, usually an adult female. Data on basic household demographics and socio-economic status, household water handling and use, sanitation, health and hygiene behaviors, and other factors thought to be related to CWP adoption were collected. Observational data related to these variables were also noted by the field data collection team.

All survey instruments were prepared in both English and Khmer before use in the study; they were pre-structured and pre-tested by back-translation from Khmer to English and used in pilot interviews to determine suitability of content and structure, reliability, and consistency. Surveys used simple, straightforward language with predominantly closed (multiple choice) questions. Individual survey questions were prepared in some cases based on input from previous questionnaires used by RDI and IDE in their own internal assessments of the CWP interventions for comparability purposes. The data collection (field) team was composed of four interviewers who were native speakers of Khmer and had experience in community health data collection in the study areas. Four weeks of pre-project interviewer training was carried out, employing mock interviews, focus groups with communities in the study area, and workshops with local NGO staff.

The main outcome variable in the cross sectional survey was filter use at the time of follow up. A logistic regression model was employed using filter use at time of follow up as a binary outcome variable. Measured covariates were tested for independent associations with the filter use at time of follow up, controlling for time since implementation coded as a categorical variable with time in 6-month blocks.

5.3.3.2 Study sites

Filters were implemented originally in three provinces in Cambodia. Interventions in Kampong Chhnang and Pursat provinces were carried out by International Development Enterprises (IDE) from July 2002. Resource Development International (RDI) conducted implementation from December 2003 in Kandal province. Households included in the study were located in 13 rural villages in the three provinces.

5.3.3.3 Definition of study population and selection of households

The study population consisted of all households originally receiving filters as part of the two large intervention projects in the three provinces of Kandal (n=1000), and Kampong Chhnang and Pursat (n=1000). Complete lists of households who received filters as part of the original interventions were compiled from information provided by the implementing NGOs. GPS coordinates or other locating details were available for some of the households. A master list of all households in the three project areas was compiled, and households were selected at random using a random numbers table. Two hundred (200) households originally receiving filters were randomly selected for follow up visits in each of the three provinces.

Inclusion criteria for the cross-sectional survey of households were: (i), being a family or other household communal unit that received a CWP through the implementation program; (ii), a family or other household communal unit still living at the same location where they received the filter; and (iii), voluntary willingness to participate in the survey. Exclusion criteria for the cross-sectional survey were: (i), the family or other household communal living unit no longer lives at the original location or (ii), unwillingness to participate in the survey.

5.3.3.4 Data collection

During the months of February and March 2006, the data collection team visited households that had originally received filters. The cross sectional survey included data collection on a variety of covariates potentially influencing the continued use of the filters under a variety of conditions and during up to 45 months of use. These included water use and handling practices and socio-economic measures, as well as elapsed time since implementation of the filter. Reasons for and estimated date of filter disuse were also solicited from respondents. The data on household water use and handling practices was gathered during an interview with the household head, defined as the adult caregiver for the children, usually an adult female. A wealth index measure of the household was used. It was based on access to electricity and an inventory of household possessions indicative of relative wealth. Data on the method of gathering water from the household storage container and on the presence of soap in the household was gathered by demonstration to the interviewer.

5.3.3.5 Data entry and management

Survey data were collected via verbally administered questionnaires and recorded onto hard copy data sheets. Households and individuals were assigned a unique code number as an identifier. During sample collection, household surveys and water samples were identified by a unique household code number assigned by the data collection team. Data were collected and original data sheets were stored at the laboratory office in bound notebooks in a locked cabinet with access only to specifically authorized project staff. Surveys and water quality data were entered regularly into a Microsoft Excel spreadsheet or Microsoft Access database and copied into Stata (version 8.1), excluding the direct personal identifiers of the study participants. All data were entered twice to ensure consistency and accuracy of data input.

5.3.3.6 Analytical approach

Observational and survey data collection at household visits were transcribed from questionnaires and double-entered into Microsoft Access. They were then exported to Microsoft Excel and Stata for analysis. Logistic regression reporting odds ratios was performed using filter use at time of follow up as a binary outcome variable, with covariates tested for independent associations with the outcome. Logistic regression analysis was also performed controlling for time since implementation, coded as a categorical variable with time in 6-month increments.

The main outcome variable in the cross sectional survey was filter use at the time of follow up. Criteria for filter use were that household members indicated regular daily use of the filter, that the filter appeared to be in good working order, and that the inside of the filter contained water or was damp from recent use. Filters that were broken, being used for another purpose, or completely dry were considered out of use.

5.3.4 Prospective cohort study

5.3.4.1 Overview

A longitudinal study was conducted using eligible participants from the cross-sectional cohort and additional households recruited from the same area. Our approach in determining the health effects of the filters among users in the households that had them was the reduction of diarrhea relative to a reference group in households that did not have filters. This was a prospective cohort study design of 80 households currently using filters and 80 households not using filters. Each household currently using a CWP (intervention, as determined by data collected in the cross-sectional survey) enrolled in the follow-up study was matched with a non-intervention (control) household (without a filter) based on area or geolocation (<1 km distant), water source, and approximate wealth. An additional 25 intervention households were recruited in Kampong Chhnang to increase the sample size to 80 households in each group. This was because an insufficient number of eligible households were identified in Kampong Chhnang & Pursat provinces using random selection of households from all households originally receiving filters. Participating households were visited three times for water sample collection and analyses. Data on diarrheal disease was gathered on two of these occasions. Data on water use and handling practices, sanitation and hygiene, and other potentially important covariates also were gathered. Stratified analyses and log-linear regression with Poisson extension of generalized estimating equations (GEE) were employed in analysis of time series data to determine the effect of the filter and water quality in the home on diarrheal disease prevalence. Prevalence proportion ratios, estimating incidence rate ratios, for diarrheal disease based on a seven day recall period among members of households with (intervention) and without (non-intervention or control) filters were used as the main outcome. Descriptive analyses of the intervention's impacts on household water quality based on levels of *E. coli* bacteria and turbidity were also performed.

5.3.4.2 Study population and selection of households

The subjects were persons who live in households using a CWP and an approximately equal number of matched (on geographic location, socioeconomic status estimate, and drinking water sources) households not using CWPs in Kandal, Kampong

Chhnang, and Pursat provinces. Participating households were randomly selected from all eligible households within the three provinces, from thirteen rural villages (Figure 5.1).

As a goal of the study was to assess effectiveness of filters over some time in use, the random selection of households was weighted within provinces to ensure that the cohort would be representative of filters in use for 0-4 years. Because interventions in each province took place during known periods, weighting the randomization by province (50% in Kandal, 25% in Kampong Chhnang, 25% in Pursat) produced eligible households with filter in use over the 4 years. Had eligible households using filters been randomly selected from all those eligible households encountered during the cross-sectional study, this would have weighted the cohort toward Kandal province and the newer interventions, as those households were much more likely to still be using their filters.

Inclusion criteria for the longitudinal study were that households (i) were willing to voluntarily participate; (ii) stored water in the home; (iii) used a CWP in a household that originally received one (intervention household) or were located in the same community, have never used a CWP, and used the same or similar water sources for household water as CWP households (reference or control household); (iv) had one or more children aged 5 years or less as a household member at the first household visit; and (vi) did not use commercial bottled water as the primary source of household potable water. Exclusion criteria were: (i) unwillingness to participate, (ii) no child less than 5 years of age in the household at the time of the first household visit, (iii) primary or exclusive use of commercial bottled water as potable water in the home, and (iv) unavailability of a consenting matched household in the other study group.

5.3.4.3 Inducements to participate

All subject households were provided with *gratis* water filters and storage containers upon completion of the study (after household interviews and water samples were collected) in return for participation in the study. Households in Kandal received equivalent filters from RDI and households in Kampong Chhnang and Pursat received IDE filters. In addition, all study subjects were provided with oral rehydration salts and instructions for use at no cost at each household visit by the study team.

5.3.4.4 Ethics

Informed consent was obtained from the appropriate family member. This was the head of household (defined as the primary caregiver for the children, responsible for household work and either responsible for or knowledgeable of household water management practices, usually an adult female) who acted as the main correspondent for the home in subsequent visits. This person was identified by asking to speak with the person who is the primary care taker and in charge of household responsibilities such as water management, cooking, cleaning, etc. The consent form was translated into Khmer and then back translated into English, and piloted to ensure clarity before use in the field. Subjects read or were read the form in Khmer by project staff. Participating householders were presented with a narrative description of the project (both written and orally) and asked to participate in the study entailing up to three household visits by the project team. Participants then signed the consent form, representing consent for all of the persons in the house. This project and its means for obtaining informed consent from participants were reviewed and approved by the Biomedical Institutional Review Board, The University of North Carolina at Chapel Hill, USA, and the Ministries of Health and Rural Development, Cambodia.

5.3.4.5 Data collection

5.3.4.5.1 Diarrheal disease

Diarrheal disease data for all household members from both study groups were collected based on 7 day recall. Interviews were conducted with the household primary caregiver on two separate occasions approximately one month apart. Interviewees were asked to report diarrheal disease (yes/no) for each member of the family in the previous 7 days including the day of the visit.

5.3.4.5.2 Water quality data

Water samples of 250 ml volume were taken from each household in the study to determine the effectiveness of the filters in reducing the concentrations of microbes present in drinking water sources. All samples were stored cold until analysis as soon as possible in the laboratory for *E. coli* and total coliform, pH, and turbidity. Samples in Kandal province were analyzed the same day; samples collected in Kampong Chhnang and Pursat provinces were stored up to 36 hours before analysis.

E. coli and total coliforms in samples were enumerated by filtering undiluted and diluted samples through 47-mm diameter, 0.45µm pore size cellulose ester filters in standard, sterile magnetic membrane filter funnels and membranes were incubated on appropriate agar or broth media-soaked absorbent pads. Agar and broth media (Rapid HiColiform media, HiMedia, M1465/M1453) detect total coliform (TC) bacteria and *E. coli* by cleavage of a chromogenic substrate for the enzyme β-galactosidase to detect total coliforms and a fluorogenic substrate for the enzyme β-glucuronidase to detect *E. coli*, producing color-specific TC colonies and *E. coli* colonies that fluoresce under long-wave UV light at 366nm (Manafi and Kneifel 1989; Manafi *et al.* 1991; Geissler *et al.* 2000). Plates were incubated for 20 – 24 hours at 37^{o}C. These methods conform to EPA Approved Method 1604 (USEPA 2002), although the culture medium used was similar but not identical to the EPA-approved MI medium. Results were reported as colony forming units (cfu) per 100 ml sample.

All samples were processed in duplicate using a minimum of two sample dilutions and positive and negative controls. Households in the intervention group were sampled for two types of water: untreated, stored household water and treated water as it was delivered via the filter tap. Samples from the control households were taken for analysis as well, and included their current drinking water and untreated water, if they use another water treatment method (e.g., boiling). Turbidity of water samples was measured in triplicate using a turbidimeter (Hach Pocket®) and the average values reported as NTU. pH of water samples also was measured in the laboratory using an electronic pH meter (Thermo Orion 290A+). Three rounds of water samples were taken from each study household over the 10 week sampling period (February 10 – April 21).

5.3.4.5.3 Additional data

In addition to the household data collected on health and water quality, additional data on potential covariates were collected during household visits. Questions were asked to determine compliance with the household water intervention (water acquisition, treatment, storage and use practices) and to document sanitation and hygiene conditions and practices. A survey of sustainability measures (e.g., frequency of filter use and cleaning, time involved in use of the filter, perception of use convenience, filter element replacement experience, etc.) was also administered to households using CWPs. These data can potentially provide important insight into the success of the intervention to date in the households where it is still being used successfully. The collected hygiene, sanitation, and water use data can be correlated with water quality and health data as potential covariates in the subsequent analysis.

5.3.4.6 Analytical approach

5.3.4.6.1 Exposures and outcomes

Water quality, health, and other household data were initially used in stratified analyses to identify trends for key exposure and outcome variables. Exposure variables of interest were presence of an intervention (CWP), water quality measures including *E. coli*/100 ml in household drinking water, and other measured covariates related to water, sanitation, and hygiene. Key outcome variables were diarrheal disease in all individuals and in children under five years of age (0-48 months at the first household visit).

5.3.4.6.2 Regression and confounding

Regression models were used to analyze diarrheal disease prevalence proportions by exposure status. Potentially confounding variables in the analytical model were (i) those that affect the exposure in the study population (e.g., factors associated with continued use of the filter); and (ii) those that are risk factors for the outcome of diarrheal disease in the control group (Last 2001). Confounders were identified based on an *a priori* change-in-effect criterion of 10%. Stratified and adjusted pooled estimates for health effect measures were reported. All analyses were performed in Stata Version 8.1 (StataCorp, College Station, TX).

5.3.4.6.3 Effect measure estimation for outcomes

Stratified analyses and log-risk regression with Poisson extension of generalized estimating equations (GEE) were employed in analysis of time series data to determine the effect of the interventions and water quality in the home on diarrheal disease (both bloody and non-bloody diarrhea) as described below. Prevalence proportion ratios for diarrheal disease based on a 7-day recall period among members of households with (intervention) and without (non-intervention or control) filters were used as the main outcome; analyses were performed using the intervention against the control group. Incidence rate ratios were also estimated from the prevalence proportion ratios based on case frequency and duration assumptions as described below.

5.3.4.6.4 Generalized estimating equations

To control for clustering of the outcomes within households and within individuals over time, a Poisson extension of generalized estimating equations (GEE) was employed in log-linear regression. GEE methods for analyzing binary outcomes over multiple time points were first described by Zeger and Liang (1986) and Liang and Zeger (1986). The model uses the marginal expectation (average response for observations with the same covariates) as a function of covariates in the analysis; correlation between individual observations is computed via a variance estimation term. The GEE model assumed that missing observations are Missing Completely at Random (MCAR) as described by Little and Rubin (2002): that the probability of an observation being missing is not related to measured or unmeasured cofactors that may be related to the exposure or the outcome. The GEE model and its application to binary longitudinal data accounting for correlation is described by Diggle *et al.* (2002).

5.3.4.6.5 Longitudinal prevalence proportion ratios

The measure of diarrheal disease risk in this study was the longitudinal prevalence ratio, the proportion of total observed time with the disease outcome in individuals. The mean longitudinal prevalence for the group is also the proportion of time with the outcome divided by the total observed time, if all group members are followed for an equal number of days (Schmidt *et al.* 2007). Because not all individuals were followed for the same amount of time in this open cohort due to missing observations, loss to follow up, death, and birth, longitudinal prevalence for individuals whose records comprised less than the 14 days of post-baseline observation were computed on a weighted basis. Because a seven day recall period was used at each household visit and no data were collected on case duration or frequency, the longitudinal prevalence calculation for individuals had a resolution of seven days.

Longitudinal prevalence is a diarrheal morbidity measure that has been shown to be strongly correlated with risk of mortality in children under 5 years of age (Morris *et al.* 1996; Schmidt *et al.* 2007). Longitudinal prevalence may be better correlated with nutritional status than incidence measures (Morris *et al.* 1996; Schmidt *et al.* 2007). Longitudinal prevalence measures also possess practical and analytical advantages over incidence measures, since case frequency and duration data (often difficult to obtain) are not collected (ibid.; Baqui *et al.* 1991; Morris *et al.* 1994). For these reasons, an increasing number of studies incorporate this measure in intervention trials (e.g., Chiller *et al.* 2006; Crump *et al.* 2004a, 2004b; Luby *et al.* 2006).

The analytical model produces estimations of longitudinal prevalence proportions that are computed from binary recall data. Estimates for longitudinal prevalence were adjusted for clustering within households and in individuals over time using a Poisson extension of Generalized Estimating Equations (GEE) as described previously. The prevalence proportion ratio (PPR) was then computed as the diarrheal prevalence proportion in this intervention group divided by the prevalence proportion in the control group.

<u>5.3.4.6.6 Incidence rate ratios</u>

Incidence rate ratios were also estimated for outcomes of diarrheal disease based on assumed case durations of three days for diarrheal disease one case per seven day period based on the binary recall data. Person time at risk was then computed as four days if an episode of diarrheal disease was reported and seven days if no cases were reported for that seven day period. Computed incidence rate ratios based on these assumptions and prevalence proportion ratios closely approximated the other.

5.3.4.7 Sample size calculations

In order to calculate a reasonable estimate for the diarrheal disease burden for the study population to use in initial sample size calculations, we used a weighted averages approach. If we accept that children under 5 have a diarrheal disease prevalence of 24.4%, and if children between 5 and 15 years of age are assigned a figure of 12%, and one-third of children under 15 are assumed to be under 5 (a conservative estimate), then the prevalence of diarrhea among those under 16 can be computed as 16.1%. If the remainder of the population is assigned a background prevalence of 8%, the overall rate of diarrheal disease in the entire population would be 11.4%. We used a baseline estimate of 12% in the sample size calculations. Diarrheal disease incidence rates (and therefore prevalence) vary with the season, with changing, seasonally-dependent water use and handling practices, with changing living conditions, and other factors.

Based on recent systematic reviews by Fewtrell *et al.* (2005) and Clasen *et al.* (2006b, 2007), which found that water quality interventions were associated with a mean 40% reduction in diarrheal disease outcomes, we based our sample size calculation on the detection of a prevalence proportion ratio (PPR) of 0.75 (that is, detection of a 25% reduction in group mean prevalence of diarrhea experienced by users versus non-users of the filter). This detectable difference of 25% is considered to be conservative, based on data published by International Development Enterprises – Cambodia (Roberts 2004), who found that the CWP was associated with a 41% decrease in diarrhea among all users versus non-users (26% among women, 55% among men) in an initial study of the intervention. Also, considering Fewtrell and Colford's (2004) reported effect of household water treatment interventions on children specifically (rate ratio = 0.59; 95% CI: 0.45 – 0.78) and in rural settings only (rate ratio = 0.53; 95% CI: 0.39 – 0.73), there is prior evidence that using a detectable PPR of 0.75 is reasonable, given this study's *a priori* inclusion criterion of households having children under 5 years of age and the filter distribution areas being largely rural.

The sample size for the study was computed as 417 individuals (in each group) to detect a 25% difference in proportions (PPR = 0.75) between the study groups with 80% power and $\alpha = 0.05$, using the methods for analysis of binary outcomes in multiple groups with repeated observations as described by Diggle *et al.* (2002). Calculations account for limited clustering within households and clustering in individuals over time, which are potentially important in the analysis of diarrheal disease data (Leon 2004; Killip *et al.* 2004). Results of power analyses in EpiSheet and EpiInfo were in general agreement with these results. Assuming 5 individuals per household, a conservative estimate, this is approximately equal to 72 households. Eighty (80) households were recruited for each study group (households with CWPs and households without them) to compensate for possible attrition.

5.4 Results

5.4.1 Cross-sectional study of filter uptake and use

5.4.1.1 Study participants and households

A total of 506 households with an average of 5.9 people per household were included in the cross sectional study (total number of persons = 2965, 52% female). Basic demographic and proxy data on household wealth was gathered and households were assigned to one of three groups: 17 households (3%) were relatively wealthy, 254 (50%) middle, and 235 (46%) poor.

A number of households (64, 11%) could not be found as GPS or other locating information was not included with the original implementation records in Kampong Chhnang and Pursat. Other households (29, 5%) had moved during the intervening years. One household (<1%) refused to participate in the study. Informed consent was obtained from 178 households in Kandal, 132 households in Kampong Chhnang, and 196 households in Pursat province. The province-weighted randomization process created a weighted overall sample toward Pursat and Kampong Chhnang. This is because filters were in use there for up to 44 months and therefore a lower number of households maintaining regular filter use was expected. Because subsequent water quality and health data collection would examine relationships between health effects and microbiological effectiveness as a function of time since implementation in this cohort, our intention was to ensure adequate numbers of in-use filters were included from the older intervention project.

Table 5.1 presents data collapsed over provinces and estimated odds ratios. Odds ratios were calculated based on all households using filters versus those not currently using filters (collapsed across province), adjusted for time in use as coded in 6 month increments. Filters that have been in use for 0 to the end of 5 months were coded as 0-5 months, and so on. Odds ratio estimates greater than one indicate a positive association between the factor and filter use; odds ratios less than one indicate a negative association.

5.4.1.2 Water use and handling practices

As households were recruited from across three provinces and several villages, a wide variety of water use and handling practices were observed, all of which varied greatly by province. During the study period of February – April (dry season), 243 households (48%) reported using surface water (lake, pond, river, stream, or canal) as a primary drinking water source (PDWS); 79 (16%) reported use of a deep well (defined here as ≥10m in depth); 152 (30%) used a shallow well; 39 (8%) used stored rainwater from the previous rainy season; and 9 (2%) of households reported using bottled drinking water. The distribution of prevalent drinking water sources varied with the region. Respondents were asked to estimate the distance to the primary drinking water source: 340 (67%) of sources were within 100m, 128 (25%) were between 100-500m, and 38 (8%) were >500m away.

All households encountered in the study used one or more water storage containers to store water inside or (more commonly) outside the home; 164 (32%) used one or more uncovered containers (unsafe storage). Containers were most commonly ceramic or concrete traditional design vessels. Respondents were asked to demonstrate the usual method of collecting water from the container for drinking. A total of 220

(43%) of the respondents dipped hands or a cup directly into the container, while 286 (57%) used a tap or a dipper which was then poured out into a cup for drinking.

5.4.1.3 Sanitation and hygiene practices

Of the 506 households included in the study, 194 (38%) had access to sanitation (either the household's own or a shared latrine). None of the households were connected to a conventional sewerage system. Sanitation access varied greatly by location; in Kandal, 71% of households had access to a latrine, versus 14% in Kampong Chhnang and 26% in Pursat. The difference here is due to the fact that study sites in Kandal were relatively wealthier and also because increasing access to sanitation had been one of RDI's efforts linked to CWP implementation in some communities. Therefore, households that had received filters were more likely to have received sanitation access as well. Respondents were asked whether and how often they and members of their family washed their hands, for example after defecating and before preparing food. 175 (35%) of household caregivers indicated that s/he washed hands "always" with soap and water at critical points such as after defecating or before preparing food. Respondents were also asked to demonstrate that there was soap in the household at the time of the visit; 339 households (67%) were able to produce it. Additionally, 114 respondents (23%) reported receiving health education relevant to water, sanitation, and hygiene. Of these, 18 (16%) reported receiving information from family and friends, 87 (76%) from a health worker or NGO, 78 (68%) from radio, 103 (90%) from television, and 1 (1%) from school. Ninety-two (92%) percent of study respondents indicated that diarrhea is a serious illness for children. Eighty-one (81%) percent of respondents reported that water is an important route of disease transmission. These basic health messages, along with instructions on proper use and regular maintenance of the filters, accompanied most implementations of the filters in the study areas.

5.4.1.4 Filter use

Of 506 households in the cross-sectional study, 156 (31%) were using the filter regularly at the time of follow up, although the proportion in use was strongly associated with the length of time elapsed between filter installation in the household and follow up (Table 5.1; Figure 5.2). If the filter was in regular (daily) use by the household, users were asked several questions about filter use such as times filling it per day and water uses. Users reported filling the filter an average of 1.8 times per day and cleaning it 2.3 times per week. 133 (86%) of households reported using the filter for drinking water only.

Respondents were also asked where they obtained the filter, whether the filter in the household at the time of the visit is a replacement filter, how much the filter cost, where they would go to buy a new filter if desired, and what an appropriate ("fair") price would be for new filters. A small number of households reported purchasing additional filters after a breakage: 11 (6%) in Kandal, 4 (3%) in Kampong Chhnang, and 6 (3%) in Pursat. Of 281 households with disused filters responding, 120 (43%) households reported a willingness to purchase an additional filter: 24 (73%) in Kandal, 20 (19%) in Kampong Chhnang, and 76 (53%) in Pursat. Respondents were asked to name an appropriate price for the CWP; the mean non-zero response (n=106) was 9500 riel (US$ 2.38): 5900r (US$ 1.48) in Kandal, 6700r (US$ 1.68) in Kampong Chhnang, and 11800r

(US$ 2.95) in Pursat. Households that were successfully using the filter on a daily basis were asked about purchasing additional or replacement ceramic filter inserts; 72% of respondents were willing to pay US$2.50, 29% were willing to pay US$4, and 26% were willing to pay US$5. The cost of replacement ceramic filter elements in Cambodia is currently in the US$2.50-$4 range.

Among respondents who previously used but are not currently using filters, factors associated with a willingness to purchase an additional filter were using a covered household water storage container (OR: 1.9, 95% CI 1.0-3.3) and having purchased a filter (versus having been given one) before (OR: 3.1, 95% CI 1.6-6.0). When respondents were asked whether household members knew where to purchase additional filters and parts, only 26% did, although distribution points are available in all three provinces within 20km from the intervention locations. Whether these distribution points were readily accessible to respondents was not clear, however, due to the high cost of transport and seasonal accessibility of roads.

5.4.1.5 Filter disuse over time

Time since implementation was calculated from the original implementation questionnaire (delivery) date where possible, followed by estimation based on the date stamped on the filter rim (manufacture date), followed by users' best estimates from interviews. Of the 477 filters for which estimates were possible, 253 (53%) were reliably dated using questionnaire or filter data and the remaining were dated by user estimation, which was probably less accurate. Broken filters were often no longer available to inspect. The manufacturing date could not be discerned on many of the oldest filters due to surface wear. Twenty-nine (29) filters, 6% of the total, could not be dated confidently by any means.

Of the 350 filters no longer in use, 328 households provided responses when asked why their filter was out of use. A total of 214 (65%) were due to filter unit breakage, either of the ceramic filter element, the spigot, or the container (Figure 5.3). The other one third of respondents gave the following reasons for disuse: the filter was too slow or otherwise unable to meet the household drinking water demand (5%); the filter had passed its recommended useful life as indicated by the NGO manufacturer, and so users assumed it was no longer effective (5%); gave or sold the filter to a friend or relative (3%); or a number of other reasons. A number of users reported having repaired the containers or taps on their own using locally-available replacement parts (buckets and taps). Figure 5.4 presents the distribution of filter time in use for all filters out of use at the time of follow up; filters were in used in households about 2 years, on average.

5.4.1.6 Factors associated with continued filter use

Figure 5.5 graphically displays observed associations between filter uptake and measured factors, together with 95% confidence intervals; odds ratios of less than one (whose confidence intervals exclude the 1.0 null value) are considered strong predictors of decreased use over time. Odds ratios greater than one (whose confidence intervals exclude the 1.0 null value) are considered strong predictors of increased use over time.

The most important predictor of the proportion of filters remaining in household use is time since implementation. The results of logistic regression indicate a declining odds of 44% every 6 months of finding a filter still in use (OR: 0.56, 95% CI 0.50-0.63).

Figure 5.2 indicates an average falloff in use of approximately 2% per month after implementation.

Other important predictors of continued filter use over time, controlling for time since implementation, were determined to be water source, investment in the technology, access to sanitation, and the practice of other water and hygiene-conscious behaviors in the household. Adjusted odds ratios for selected measured parameters' associations with continued filter use are presented in Table 5.1 and Figure 5.5.

With respect to water source, households that reported groundwater use from deep wells (defined here as ≥10m) were less likely to use the filter (OR: 0.38, 95% CI 0.18-0.79) after controlling for time since implementation. Conversely, a positive association was observed between surface water use and continued filter use (OR: 1.7, 95% CI 1.1-2.7). Similar associations were not observed between continued filter use and the use of covered versus uncovered wells, method of withdrawing water from wells, estimated distance to main drinking water source, method of withdrawing water from the household water storage container, or use of stored rainwater or bottled water during the study period (the dry season).

Other potentially important demographic and socio-economic predictors of filter use were also examined as a part of the cross sectional study. Sex of household head (OR 1.1, 95% CI 0.63-2.0) and reported household income (OR: 0.68, 95% CI 0.42-1.1) were not associated with the outcome of continued filter use after controlling for time since implementation.

Cash investment, at any level, by the household in the filter was associated with continued filter use (OR: 2.1, 95% CI 1.2-3.7) versus receiving the filter *gratis*. Cash payments for the filters ranged from 1000 to 10,000 riel (US$0.25 – $2.50). No clear trend was observed between filter use and the level of cash investment.

Respondents who reported other safe water, sanitation, and hygiene practices were more likely to be using the filter at the time of follow up. For example, access to a household's own or shared latrine (OR: 2.4, 95% CI 1.5-4.0), the household caregiver reporting that s/he always washed hands with soap and water at critical points such as after defecating or before preparing food (OR: 1.6, 95% CI 1.0-2.6), and the presence of soap in the household (OR: 1.7, 1.0-3.0) were all observed to be positively associated with filter use after controlling for time since implementation. The practice of covering the household water storage container (safe storage) may also be positively associated with continued filter use (OR: 1.6, 95% CI 0.94-2.7). No clear association was observed between filter use and caregivers reporting water-related health and hygiene education (OR: 0.74, 95% CI 0.42-1.3). Observed associations do, however, suggest a relationship between filter use and knowledge of positive household health and hygiene practices.

5.4.1.7 Time in use

Of 350 total disused filters, 317 were dated based on original installation records, the lot number and date on the filter rim, or respondents' estimates. Users were asked to approximate, if possible, the date that the family stopped using the filter to the nearest month. Distribution of time-in-use data in 6 month increments is presented in Figure 5.4.

5.4.2 Prospective cohort study

5.4.2.1 Study participants and households

Subjects for the longitudinal water quality and health study were identified and recruited from the cross-sectional study cohort, who in turn were identified from records on the initial implementation of the filters. Eligible and consenting households from the cross-sectional survey were immediately recruited into the longitudinal cohort for further water quality and health data collection. A further 25 households in Kampong Chhnang were recruited from outside the cross-sectional cohort to increase the sample size to 80 total households meeting criteria for intervention households, as required from *a priori* sample size calculations.

Demographic and other characteristics of the households included in the longitudinal study are presented in Table 5.9, by study group. One hundred fifty-nine (159) households completed both follow up visits, with a total of 1007 people (mean household size: 6.3, median age: 18, range: 1-84 years at the time of first household visit. Because having a child ≤5 years of age was a longitudinal study inclusion criterion for households. the age distribution in the two household groups (intervention and non-intervention) may not be representative of the source population in the study villages. One intervention household (1%) was lost to follow up. All households were located in Kandal, Kampong Chhnang, and Pursat provinces in villages where the initial CWP implementations took place.

5.4.2.2 Data stratified by study group

The intervention group, those using CWPs regularly, contained 79 households and 528 individuals (6.68 people per household, 53% female, 15% under the age of five). Of these households, 40 (51%) were located in Kandal, 18 (23%) in Kampong Chhnang, and 21 (27%) in Pursat. Respondents were asked more detailed questions about socioeconomic factors (including a direct estimate of household income) and education for the primary caregiver in the household. Reported total household income in 13 (16% of) households was <$50, in 41 (52% of) households $50-$99, in 15 (19% of) households $100-$149, and in the remaining 10 households (12%) $≥150. Education levels for the primary caregiver (usually an adult female) in the intervention group were reported as: 19 (24%) had some or all primary school, 59 (75%) had some or all secondary school, and 1 (1%) had post-secondary training.

The control group (without filters) contained 80 households and 479 individuals (5.98 people per household, 51% female, 18% under the age of five). Of these 80 households, 40 (50%) were located in Kandal, 20 (25%) in Kampong Chhnang, and 20 (25%) in Pursat. Respondents were asked more detailed questions about socioeconomic factors (including a direct estimate of household income) and education for the primary caregiver in the household. Of the 80 control households, 19 (24%) reported total household monthly income as <$50, 39 (49%) reported in the $50-$99 range, 18 (22%) in the $100-$149 range, and the remaining 4 households (5%) ≥$150. Education levels for the primary caregiver (usually an adult female) in the control group were reported as: 27 (34%) had some or all primary school, 52 (65%) had some or all secondary school, and 1 (1%) had post-secondary training.

5.4.2.3 Water use and handling practices

Intervention households (including those not included in the cross-sectional study (from Kampong Chhnang) were asked about water use and handling practices, hygiene and sanitation, and potentially important covariates as in the cross-sectional study. Results are presented in Table 5.9. During the study period of February – April (dry season), 43 households (54%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 13 (16%) reported use of a deep well (defined here as ≥10m in depth); 19 (24%) used a shallow well; and 6 (8%) used stored rainwater from the previous rainy season. 23 (29%) used one or more uncovered water storage containers. Respondents were asked to demonstrate to the interviewer the usual method of collecting water from the container for drinking; 35 (44%) of respondents dipped hands or a cup directly into the container, while 44 (56%) used a tap or a dipper which was then poured out into a cup for drinking.

Control households were asked about water use and handling practices, hygiene and sanitation, and potentially important covariates as in the cross-sectional study. Results are presented in Table 5.9. During the study period of February – April (dry season), 48 households (60%) reported using surface water (lake, pond, river, stream, *prek*, *boeng*, or canal) as a primary source of drinking water; 12 (15%) reported use of a deep well (≥10m in depth); 22 (28%) used a shallow well; and 2 (3%) used stored rainwater from the previous rainy season. Thirty (30) (37%) used one or more uncovered water storage containers. Respondents were asked to demonstrate the usual method of collecting water from the container for drinking; 30 (38%) of respondents dipped hands or a cup directly into the container, while 50 (62%) used a tap or a dipper which was then poured out into a cup for drinking.

5.4.2.4 Sanitation and hygiene practices

Of the 79 households in the intervention group, 44 (56%) had access to sanitation (either the household's own or a shared latrine). None of the households were connected to a conventional sewerage system. Respondents were asked whether and how often they and members of their family washed their hands, for example after defecating and before preparing food. Of the 79 households, 33 (42%) of respondents indicated that hand washing was practiced by all members of the household "always" at critical points with soap and water. Respondents were also asked to demonstrate that there was soap in the household at the time of the visit; 62 intervention households (77%) were able to produce it.

Of the 80 households in the control group, 35 (44%) had access to sanitation (either the household's own or a shared latrine). None of the households were connected to a conventional sewerage system. Respondents were also asked whether and how often they and members of their family washed their hands, for example after defecating and before preparing food. Of 80 household respondents, 29 (36%) indicated that hand washing was practiced by all members of the household "always" at critical points with soap and water. Respondents were also asked to demonstrate that there was soap in the household at the time of the visit; 70 control households (87%) were able to produce it.

5.4.2.5 Water quality data

5.4.2.5.1 Mean pre- and post-treatment sample data

Household drinking water quality data for all households are presented in Table 5.2. Sixty-six percent (66%) of CWP-treated water samples were under 10 *E. coli*/100 ml, with 40% of samples having <1 *E. coli*/100 ml. Sixty-two percent (62%) of household drinking water samples from control households contained relatively high levels of *E. coli* (≥101 cfu/100 ml *E. coli*) versus 14% of samples from intervention households. Summaries of arithmetic and geometric means of total coliform, *E. coli*, and turbidity counts in intervention household samples (both treated and untreated water) are presented in Tables 5.3 and 5.4. The arithmetic mean *E. coli* concentration in filter-treated water was 160 cfu/100 ml (95% CI 61-260) against 3000 cfu/100 ml (95% CI 2000-4000) in control households. The geometric mean *E. coli* concentration in filter-treated water was 15 cfu/100 ml (95% CI 9.9-22) compared to 570 cfu/100 ml (95% CI 430-750) in control households. Figure 5.6 shows the distribution of *E. coli*, TC, and turbidity data in treated and untreated water samples.

5.4.2.5.2 $\log_{10}$ reduction values (LRVs)

The $\log_{10}$ reduction values of *E. coli* in treated versus untreated water are presented as standard measures of technology performance (Table 5.5). Based on 203 total samples over three sampling rounds, the arithmetic mean $\log_{10}$ reduction of *E. coli* using the CWP was 1.3 (95% CI 1.10-1.51, n=203) or 95.1%. The arithmetic mean $\log_{10}$ reduction of total coliforms using the CWP was 1.0 (95% CI 0.82-1.22, n=203) or 90%. The arithmetic mean reduction in turbidity was 73% (95% CI 68%-78%, n=203). The geometric mean $\log_{10}$ reduction of *E. coli* using the CWP was 1.7 (95% CI 1.5-1.9, n=203), or 98%. The geometric mean $\log_{10}$ reduction of total coliforms using the CWP was 1.2 (95% CI 1.0-1.4, n=203) or 94%. The geometric mean reduction in turbidity was 70% (95% CI 65%-75%, n=203); Figure 5.7 shows these data graphically for all samples with the arithmetic means as point estimates.

5.4.2.5.3 Stored boiled water

Many households reported using boiled water for some or all of the household drinking water (55% of control households, 33% of intervention households), although in practice this water is often reserved for adults only and usually used to make tea. In order to compare stored, treated water quality between the CWP and stored, boiled water, a total of 84 boiled water samples were taken and processed for *E. coli*, total coliforms, turbidity, and pH along with other water samples. The $\log_{10}$ reduction value distribution for the two treatment methods are similar, including the percentage of samples having worse quality than the untreated (raw) water stored in the home as determined by *E. coli* counts (Table 5.8).

The arithmetic mean $\log_{10}$ reduction of *E. coli* using the CWP was 1.3 (95% CI 1.10-1.51, n=203), or 95.1%, versus 1.7 for boiling (95% CI 1.5-2.0, n=84) or 98.2%. The geometric mean $\log_{10}$ reduction of *E. coli* using the CWP was 1.7 (95% CI 1.5-1.9, n=203), or 98%, versus 2.0 for boiling (95% CI 1.8-2.3, n=84) or 99%. The arithmetic mean turbidity in stored, boiled water samples was 8.6, versus 1.5 for samples taken from CWPs.

5.4.2.5.4 Filter effectiveness and time

There did not appear to be a strong correlation between filter effectiveness and time in use (Tables 5.6 and 5.7; Figure 5.8). Microbiological effectiveness as indicated by *E. coli* LRVs or by *E. coli* quantification of filter effluent revealed no change in trend of performance level in samples taken from filters representing a broad range of time in use.

5.4.2.6 Diarrheal disease

5.4.2.6.1 Impacts of filter intervention on diarrheal disease

Details of the cohort included in the health impact assessment are presented in Table 5.9. A clear difference in diarrheal disease prevalence was observed in filter (intervention) households compared to control (non-filter) households, in all age groups, both sexes, and in each province (Tables 5.10 and 5.11), indicating a strong protective effect of the intervention. The adjusted prevalence proportion ratio (PPR) effect estimate for all ages was 0.54 (95% CI: 0.41-0.71), corresponding to a reduction in diarrheal disease of 46%. Incidence rate ratios were approximated from the diarrheal recall data and are calculated for comparison, based on case duration and frequency assumptions. The estimates for diarrheal disease impact of the CWP were adjusted for no covariates as none produced a ≥10% change-in-estimate of effect (a greater than or equal to 10% change in the overall estimate when adding variables to the model), including socio-economic status as indicated by household income and other measured parameters; household demographics; access to sanitation; measured hygiene practices and observations; and other variables. A greater estimate of effect was observed where the background (control) prevalence proportion of individuals reporting diarrhea was higher.

5.4.2.6.2 Diarrheal disease and water quality

Diarrheal disease (7 day recall) was also examined as an outcome with water quality (*E. coli* cfu/100 ml) as the exposure variable, adjusting for presence of the intervention and clustering of the outcome between individuals in the same household. No correlation was observed between reported diarrhea and increasing levels of *E. coli*. Results of log-linear regression are presented in Table 5.12.

Compared to a reference level of 1.0 (adjusted prevalence proportion ratio from GEE analysis) within the *E. coli* stratum of <1 *E. coli*/100 ml, from 1-10 *E. coli*/100 ml the prevalence proportion ratio was computed as 1.0 (95% CI 0.66-1.7). From 11-100 *E. coli*/100 ml, the PPR was 1.0 (95% CI 0.82-1.2). Within the stratum of samples falling in the range of 101-1000 *E. coli*/100 ml, a PPR of 1.1 (95% CI 0.95-1.2) was computed. For samples yielding over 1000 culturable *E. coli* per 100 ml sample, the stratum-specific PPR was 0.95 (95% CI 0.84-1.1).

5.4.2.6.3 Other factors related to diarrheal disease

Independent associations between diarrheal disease and other measured cofactors were analyzed, displayed graphically in Figures 5.9 and 5.10. These estimates and confidence intervals were adjusted for clustering within households, in individuals over time, and for the presence of the intervention (CWP). Positive associations with diarrheal disease were observed with the following factors: living in the poorest, most rural province, Pursat (PPR = 1.5, 95% CI 1.2 – 2.0 for all ages; PPR = 1.9, 95% CI 1.2 – 3.0 for under 5s); being under 5 years of age (0-48 months) at the start of the study (PPR = 2.5, 95% CI 1.9 – 3.3); and the observation of human or animal feces inside the household at one or more visits (PPR = 1.5, 95% CI 1.0 – 2.2) (Figures 5.9 and 5.10).

Adjusting for clustering within households and within individuals over time, negative associations with diarrheal disease were observed with the following factors: living in the wealthiest, peri-urban province, Kandal (PPR = 0.65, 95% CI 0.49 – 0.85 for all ages; PPR = 0.63, 95% CI 0.39 – 1.0 for under 5s); having more than the mean number of people in the household (greater than 7 individuals, PPR = 0.68, 95% CI 0.52-0.89); living in a house that is constructed primarily of brick or concrete, a positive wealth indicator (PPR = 0.35, 95% CI 0.16 – 0.78); the household caregiver having attained at least primary school education (PPR = 0.61, 95% CI 0.46 – 0.81 for all ages; the use of rainwater as a primary (non-exclusive) drinking water source during the study (PPR = 0.77, 95% CI 0.58 – 1.0); access to a latrine (PPR = 0.56, 95% CI 0.43 – 0.74 for all ages; PPR = 0.55, 95% CI 0.34 – 0.90 for under 5s); and the adult caregiver reporting that she or he washes hands with soap "always" at critical points such as after cleaning a child or before preparing food (RR = 0.73, 95% CI 055 – 0.98, all ages (Figures 5.9 and 5.10).

5.5 Discussion

5.5.1 Factors associated with long term filter use

Results suggest that ceramic water filters are more likely to be used by households that (i) already have some knowledge of safe water, sanitation, and hygiene practices; (ii) invest in (purchase) the technology; (iii) use surface water sources for drinking water; and (iv), do not use deep wells (≥10m) as a primary source of drinking water. The high rate of breakage of the filters suggests that the availability of replacement parts and access to or awareness of distribution points may limit the sustainability of ceramic filter intervention efforts. This is because a predicted 2% of filters may fall into disuse each month after implementation due primarily to breakage. It is recognized, however, that NGO filter (hardware) models and implementation strategies are improving and this study accounts only for those in already in use for varying periods of time up to 4 years. Despite the declining use of the intervention, user satisfaction with the filters was generally very high, and a high percentage of users reported a willingness to purchase additional filters or replacement parts. Time in use for filters in households was about 2 years, on average, before disuse (Figures 5.2 and 5.4). This suggests that filters can be used reliably for extended periods and also that users valued the filters enough to keep using them, usually until breakage. Greater availability and accessibility of spare parts, especially the ceramic filter elements themselves, should enhance the sustainability of the intervention.

Because these data are cross-sectional for use data from several interventions over 44 months, it would be incorrect to describe the 2% decline in use per month post-implementation as a falloff "rate", although evidence (Figure 5.2) suggests that there is a linear association between use and time that transcends differences in implementation models or other locally variable factors. No filter implementations took place where users had access to replacement filters or parts, so these data may not represent situations where replacements are available to users.

The declining use of 2% per month is consistent with the findings of one other ceramic filter implementation study that reported a decline in use of approximately 20% after 9 months in Bolivia in the absence of replacement filters (Clasen *et al.* 2006a). Several studies have examined uptake of interventions for household water use and safe storage by measuring continued use of the technology or method (Luby *et al.* 2001; Mong *et al.* 2001; Parker *et al.* 2006; Clasen *et al.* 2006a). Often uptake and use of technologies is a complex process that involves many socio-cultural factors (Wellin 1955; Rogers 2003). There is some evidence that this is a major factor limiting the success of household water treatment, for all technologies. More research is needed on the long term sustainability of this strategy for providing access to safe water, although some method of household water treatment may be the only option for many lacking access to this basic need.

Anecdotal evidence in the study region suggests low flow rates and rapid clogging of ceramic filters are associated with the use of groundwater from deep wells, which suggests these factors may explain the lower use of CWPs among those using deep wells as a primary water source. This may be the result of insoluble ferric (Fe^{3+}) iron formation from dissolved Fe^{2+}, which occurs in high concentrations in many Cambodian groundwaters (Feldman *et al.* 2007). The same association was not observed with households reporting use of shallow wells (OR: 0.91, 95% CI 0.50-1.7), possibly due to Fe oxidation and precipitation that occurs in the water of open wells before water is drawn. Interviews with participating study households confirmed that water from deep well sources is also perceived to be potable without further treatment.

5.5.2 Impacts of filter intervention on household drinking water quality

Use of a CWP was associated with a substantial improvement in drinking water quality at the household level compared to a matched control group not using filters, reducing *E. coli* by a mean of 98% with reductions as high as 99.99%.

5.5.3 Filter effectiveness and time

There does not appear to be a change in the relationship between filter effectiveness and time, supporting the hypothesis that the filters can maintain effectiveness for up to 4 years (and potentially longer) in household use. For this reason and because 5% of households surveyed indicated filter "expiration" as a reason for not continuing to use it (Figure 5.3), existing recommendations by manufacturers and implementers on filter replacement (usually every 1-2 years) should be reconsidered. Further work is needed to evaluate filter performance against other microbes, including human pathogens, over time and for durations of more than four years.

5.5.4 Boiling

Results suggest that filters were as effective as boiling for the reduction of *E. coli* in household drinking water. CWPs should not, however, be marketed as a replacement technology for boiling until more extensive studies have shown that the CWP is also consistently effective against viruses and protozoan parasites. Use of the CWP was associated with a greater reduction in turbidity over boiling. Interviews with users suggest that the improved aesthetic properties of the filter-treated water as well as its lower comparative cost make the CWP an attractive option for drinking water treatment, findings that agreed with those of Roberts (2004).

5.5.5 Recontamination

The treated water may be susceptible to re-contamination, however, as are all household water treatment methods, including the most microbiologically effective method (boiling), as was observed in this study. Results suggest that, although both boiling and treatment via CWPs can improve water quality, there is a potential risk of recontamination of water through unsafe filter handling and water storage practices. Education and training in proper technology use and safe water storage practices should be part of any effective program to improve water quality in the home. Compliance has been shown to be positively associated with health gains due to water quality improvements at the point of use (Clasen *et al.* 2006b).

These results are consistent with studies (e.g., Wright *et al.* 2004 and Jensen *et al.* 2002) showing that recontamination of stored water in the home could significantly impact the quality of potable water used in the household. While improving the technology is important, it must also be stressed that proper use of the technology is as critical as the technology itself. Behavioral change and education "software" accompanying interventions may increase proper use of the filters and result in lower levels of recontamination and possibly lower risks of waterborne diarrheal disease.

5.5.6 Log_{10} reduction values (LRVs) and filter performance

A common method for evaluating performance is the computation of $\log_{10}$ reduction values (LRVs; Table 5.5; Figures 5.7 and 5.8), which correspond to percent reductions of some measure (e.g., *E. coli*/100 ml, turbidity) due to treatment. Treated water concentrations greater than untreated water concentrations for the indicator under study (*E. coli*, cfu/100 ml) lead to negative $\log_{10}$ reduction values (LRVs). Out of 79 filters in the intervention group, 46 were observed to have negative LRVs at one or more visits: 20 (50%) filters in Kandal, 10 (56%) in Kampong Chhnang, and 10 (48%) in Pursat. Nine filters (11%) failed at multiple time points.

Filters may produce water of worse apparent quality than the untreated (raw) water, resulting in negative $\log_{10}$ reductions of *E. coli*. These results may be due to changing *E. coli* levels over time (either die-off or regrowth, Desmarais *et al.* 2002), a change in source water from that used to produce filtrate, *in situ* inactivation of the indicator due to exposure of the filter or household stored water to sunlight or some other process, or other factors.

Another possible explanation for negative LRVs is filter recontamination during use, for example due to improper cleaning or handling. While the storage system used with the ceramic water filters is generally thought to be safe (closed storage container, water dispensed via a tap), contamination of the filter could be introduced through frequent cleaning or cleaning with a contaminated cloth. As indicated previously, *E. coli* in filtered water could also multiply during storage. Seventy-seven (77%) percent of households in the intervention group reported cleaning the filter element with a cloth or *krama* (n=79) and 71% reported cleaning the storage container with a cloth or *krama* (n=79). Eighty-nine percent (89%) of users reported cleaning the filter and 29% reported cleaning the storage container with raw water only, with the remainder using soap and raw water. The mean reported frequency of cleaning the filter was 2.3 times per week. *Kramas* are multi-use traditional cloths used around the household in Cambodia, which are thought to be important vectors for fecal microbes and possibly other pathogens. Cleaning the filters with these cloths may be one means of compromising the filter and recontaminating the stored water. No clear associations were observed, however, between the probability of negative LRVs (achieving <0 $\log_{10}$ reduction of *E. coli*) and measured parameters such as reported frequency of use, frequency of cleaning, method of cleaning the filter or bucket, number of people in the household, manufacturer, time in use, or other factors as determined by logistic regression.

5.5.7 Diarrheal disease

5.5.7.1 Effects of the intervention on diarrheal disease

Use of the filters was associated with a reduced diarrheal disease burden during the study, with diarrheal prevalence in the intervention group being only 54% of that in the control (non-filter) group (PPR = 0.54, 95% CI 0.41-0.71). These effects were not significantly different across age, sex, or province categories. Results suggest that the CWP does reduce the burden of diarrheal disease in users versus non-users. Estimates were not adjusted for any measured covariates as none produced a ≥10% change in effect when added to the model, which was the a priori criterion for the identification of confounding.

5.5.7.2 Diarrheal disease and water quality

No association was observed between *E. coli* in household drinking water and diarrheal disease after adjusting for presence of the intervention and for clustering of the outcome between household members. Results suggest that the presence of *E. coli* in household drinking water, even at very high levels (>1000 cfu/100 ml), may not be strongly correlated with diarrheal disease outcomes.

The water quality parameters used in this study are known to vary by season and diurnally as functions of temperature, available nutrients, exposure to sunlight, and other factors, so water quality data from single sampling events may not be representative of drinking water quality in use by the household. At best, these data represent a series of point estimates of *E. coli* in water that may approximate levels of waterborne pathogen concentrations across space and time. For this reason, positing associations between water quality data based on *E. coli* levels and the outcome of diarrheal illness may be tenuous. Other studies have failed to explicitly observe this association (e.g., Jensen *et al.* 2004). Gundry *et al.* (2004) concluded that there was no clear association between levels of indicator bacteria (*E. coli*, thermotolerant coliforms) and diarrhea in a review of intervention trials. Similarly, Moe *et al.* (1991) found no relationship between diarrheal illness rates and good quality (<1 *E. coli*/100 ml) versus moderately contaminated water (2-100 *E. coli*/100 ml) in a field study from the Philippines.

Possible explanations for these results are that (i) *E. coli* is not a sufficiently good indicator of waterborne diarrheal disease in the context of this study (dry season, stored household drinking water in rural Cambodia); (ii) that measured health impact data (diarrheal disease occurrence) are misleading due to a placebo effect of the filters (e.g., Hellard *et al.* 2001; Colford *et al.* 2002) and/or that drinking water may not be an important route of exposure to diarrheagenic pathogens in the population at the time of the study; (iii) that health data are biased due to recall (Boerma *et al.* 1991) or reporting issues (Thomas and Neumann 1992); or that (iv) the measured *E. coli* concentration from the time of sampling is not representative of the drinking water quality consumed by all the household members during the previous 7 days.

This study assumes that the filters do improve water quality and that in doing so they reduce waterborne disease. Although improvements in water quality are measured by reduction of *E. coli* in drinking water, it may not follow that reductions in diarrhea result from reductions in *E. coli* in water. Indeed we assume that diarrhea and *E. coli* in water are not well correlated based on previous studies (e.g., Moe *et al.* 1991). The reduction in diarrheal disease overall is linked to the reduction of all pathogens in water, which may be only poorly indicated by *E. coli* itself.

5.5.7.3 Diarrheal disease and other covariates

A range of water, sanitation, and hygiene-related factors were associated with the outcome of diarrheal disease in this study. After adjusting for the presence of the intervention (CWP), negative associations (decreased diarrheal disease) were observed for diarrhea with handwashing, sanitation, maternal education, province, a wealth indicator, and number of people in the household. Positive associations (increased diarrheal disease) were observed with age (under 5 years of age), hygiene as indicated by presence of feces in the household at the time of visit, and province.

5.5.8 Study limitations

This study was limited primarily by its short duration, which did not allow for sampling to account for seasonal changes in water quality and health. There was also the potential for selection bias in this study design. In some cases the remoteness of sampling sites contributed to delayed delivery of water quality samples, potentially impacting the reliability of these data. These are briefly discussed below.

5.5.8.1 Seasonal effects

Seasonal effects on diarrheal disease prevalence or microbiological water quality were not accounted for in this study, which was conducted entirely in the dry season. Annual rainfall is not evenly distributed throughout the year in Cambodia: during the rainy season (June – October) it rains between 15 and 30 cm per month, with dry season (December – March) averages of 0-5 cm per month. Water use practices, water treatment practices, diarrheal disease rates, and the presence of microbial pathogens and indicators in potential drinking water sources can vary greatly depending upon the season. In the study areas, diarrheal disease prevalence may be higher in the dry season, when users shift away from the use of relatively safe rainwater to relatively unsafe surface water sources, and because lower water availability in the dry season may limit hygiene practices. Longitudinal studies such as this one that attempt to capture the protective effect of an intervention on diarrheal disease are subject to possible effect measure modification by seasonal effects, resulting in very different quantitative findings or even outcomes over the course of a year as conditions change.

5.5.8.2 Selection bias

Selection bias can threaten the validity of studies when study inclusion is predicated upon technology uptake and use. In this study, selection bias may have arisen because households that received filters or were still using the filters after some intervening time may have been fundamentally different from those in the control group, who never received filters. Control selection was used to counter this potential bias by matching intervention and control households by potentially important characteristics such as socio-economic status and water source, although this bias may not have been eliminated wholly from the study. Although measured parameters could be accounted for in the analysis, there is a possibility that covariates that are associated with differences between study groups were not measured. Other or better socioeconomic data; human behaviors that may be linked to water quality or health; or other factors related to water, sanitation, and hygiene could have been measured and linked with important differences between the groups included in this study. In this study, selection bias of this type would tend to bias results away from the null hypothesis of no effect of the filter intervention on diarrheal disease, since households using the filter successfully over long periods may be more conscientious, more aware of water and sanitation issues, and/or more proactive in environmental health-related positive behaviors.

5.5.8.3 Sample delivery and processing

Although every effort was made to ensure that samples were transported quickly to the laboratory for analysis, there were field samples (approximately 6% of the total) that were not processed within 36 hours (up to 60 hours) from the point of sampling. In all cases samples were kept on ice in a cooler from the point of sampling. ANOVA of *E. coli* and total coliform counts in samples as a function of hours between sampling and analysis did not suggest any difference in sample means coded within blocks of twelve hours from analysis ($p = 0.23$ for *E. coli*; $p = 0.66$ for total coliform).

5.6 Conclusions

Findings of this study are summarized below.

- The rate of filter disuse was approximately 2% per month after implementation, due largely to breakages. There was a strong association between filter use and time since implementation.
- Controlling for time since implementation, continued filter use over time was most closely positively associated with related water, sanitation, and hygiene practices in the home, cash investment in the technology by the household, and use of surface water as a primary drinking water source. Continued use of the filters was associated with awareness of other water, sanitation, and hygiene behaviors and improvements, suggesting possible synergies between CWP implementation and successful long-term use by users.
- Continued use of the filters was positively associated with cash investment in the technology, although continued use was not observed to be closely related to price in this study.
- The filters reduced *E. coli*/100 ml counts by a mean 98% in treated versus untreated household water, although demonstrated filter field performance in some cases exceeded 99.99%.

- Microbiological effectiveness of the filters was not observed to be closely related to time in use. Since time in use was not shown to be strongly related to performance, recommendations that users replace the ceramic filter elements every one or two years (as is current practice) may not be necessary.
- The filters can be highly effective in reducing microbial indicator organisms but may be subject to recontamination, probably during "cleaning" with soiled cloths; Recontamination of the filter and storage receptacle through improper handling practices is a real threat to the effectiveness of this technology.
- The filters were associated with an estimated 46% reduction in diarrhea in filter users versus non users (PPR: 0.54, 95% CI 0.41-0.71).
- No association was observed between measured *E. coli* in household drinking water and diarrheal disease, after adjusting for presence of the intervention and clustering within households.
- Other significant associations were observed with water, sanitation, and hygiene-related factors that were also measured as part of the study, such as handwashing, education, measures of SES, and access to sanitation, after adjusting for the presence of the intervention. Using boiled drinking water, handwashing, access to sanitation, and other factors were also associated with reduced diarrheal disease, although more analytical work is needed to sort out these associations and potential confounders.

	Using filter[a] at time of follow up (156 households)	Not using filter at time of follow up (350 households)	OR (95% CI) Adjusted[b]
Caregiver reported receiving health education[c]			
Yes	31 (20%)	83 (24%)	0.74 (0.42-1.3)
No	125 (80%)	267 (76%)	
Soap observed in household[d]			
Yes	119 (76%)	220 (63%)	1.7 (1.0-3.0)
No	37 (24%)	130 (37%)	
Purchased filter[e]			
Yes	112 (72%)	99 (28%)	2.1 (1.2-3.7)
No	44 (28%)	251 (72%)	
Living on less than 1 USD per day per person in household[f]			
Yes	49 (31%)	186 (53%)	0.68 (0.42-1.2)
No	107 (69%)	164 (47%)	
Access to sanitation[g]			
Yes	102 (65%)	92 (26%)	2.4 (1.5-4.0)
No	54 (35%)	258 (74%)	
Safe storage practices observed[h]			
Yes	118 (76%)	224 (64%)	1.6 (0.94-2.7)
No	38 (24%)	126 (36%)	
Caregiver reports washing hands "always"[i]			
Yes	76 (49%)	100 (29%)	1.6 (1.0-2.6)
No	80 (51%)	250 (71%)	
Main drinking water sources during study (dry season)[j]			
Surface water	98 (63%)	145 (41%)	1.7 (1.1-2.7)
Groundwater	41 (26%)	190 (54%)	0.56 (0.34-0.94)
Deep well (≥10m)	14 (9%)	65 (19%)	0.38 (0.18-0.79)
Shallow well	27 (17%)	125 (36%)	0.91 (0.50-1.7)
Rainwater	23 (15%)	16 (5%)	1.4 (0.64-3.0)
Bottled water	2 (1%)	7 (2%)	0.53 (0.08-3.4)
Observed method of collecting household stored water[k]			
Use hands	70 (45%)	150 (43%)	0.90 (0.56-1.4)
Pour, tap, or designated dipper	86 (55%)	200 (57%)	
Months since implementation[l]			
0-5	49 (31%)	8 (2%)	0.56 (0.50-0.63) (per 6 month increase)*
6-11	12 (8%)	3 (1%)	
12-17	16 (10%)	16 (5%)	
18-23	32 (21%)	31 (9%)	
24-29	14 (9%)	30 (9%)	
30-35	6 (4%)	29 (8%)	
36-41	11 (7%)	112 (32%)	
42-48	14 (9%)	96 (27%)	

a. Regular (daily) use, as determined by interview and by visual inspection. May not add to 100% due to rounding.
b. Odds ratios adjusted for time since implementation coded as a categorical variable in 6 month blocks, except *.
c. Water, health, hygiene, or sanitation education from any source (school, NGO, media, etc).
d. Respondents were asked to demonstrate that soap was present in the household.
e. Any price. Prices paid for filters ranged from 1000 – 10,000 riel (US$0.25 – $2.50). Actual cost is US$4-$8.
f. Based on self-reported monthly income and number of members in household.
g. Shared or own latrine.
h. Safe storage was defined as using a covered or narrow mouth water storage container and a designated water dipper to collect water.
i. Caregiver responds that s/he washes hands "always" with soap at critical points such as after defecating.
j. Multiple answers possible.
k. Respondents were asked to demonstrate their usual method of gathering water from the storage container.
l. Based on NGO records from the original installation, the manufacturing date stamped onto the filter, or users' estimates.

Table 5.1. Data summary and estimated odds ratios for selected factors. Odds ratios are adjusted for time elapsed since implementation.

	Number (percentage[a]) of all samples by E. coli *concentration of household drinking water[b]*					
	<1 (cfu/100 ml)	1-10 (cfu/100 ml)	11-100 (cfu/100 ml)	101-1000 (cfu/100 ml)	1,001+ (cfu/100 ml)	Total samples[c]
Control households	40 (18%)	2 (1%)	42 (19%)	80 (35%)	62 (27%)	226
Kandal	15 (13%)	2 (2%)	24 (21%)	46 (39%)	30 (26%)	117
Kampong Chhnang	13 (24%)	0	7 (13%)	15 (28%)	19 (35%)	54
Pursat	12 (22%)	0	11 (20%)	19 (35%)	13 (24%)	55
Intervention households	89 (40%)	54 (26%)	38 (18%)	23 (11%)	7 (3%)	211
Kandal	53 (47%)	32 (29%)	17 (15%)	9 (8%)	1 (1%)	112
Kampong Chhnang	18 (42%)	12 (28%)	6 (14%)	4 (9%)	3 (7%)	43
Pursat	18 (32%)	10 (18%)	15 (27%)	10 (18%)	3 (5%)	56

a. Percentages within strata may not add up to 100% due to rounding.
b. Samples were filter effluent in intervention households, stored household drinking water for control households. Households were asked to provide a sample of the water that the family was drinking at the time of visit.
c. Incomplete data for 14 (6%) control households and 29 (12%) intervention household samples.

Table 5.2. Observed levels of *E. coli* (cfu/100 ml) in household drinking water by study group.

	Water quality data[a], arithmetic means (untreated water)			*Water quality data[a], arithmetic means (treated water)*		
	TC/100 ml	*E.coli*/100 ml	Turbidity (NTU)	TC/100 ml	*E.coli*/100 ml	Turbidity (NTU)
All provinces	14,000	2300	8.70	2000	160	1.53
Kandal	10,000	1100	2.71	1200	77	0.78
Kampong Chhnang	22,000	3300	4.10	2800	31	1.65
Pursat	14,000	3700	24.3	3000	23	3.25

a. Data from intervention households, raw (untreated) water and filtered (treated water) samples from 3 sampling rounds, February-April 2006.

Table 5.3. Arithmetic mean total coliform and *E. coli* counts (cfu/100 ml) and turbidity for samples taken in intervention households (untreated and treated water).

	Water quality data[a], geometric means (untreated water)			*Water quality data[a], geometric means (treated water)*		
	TC/100 ml	*E.coli*/100 ml	Turbidity (NTU)	TC/100 ml	*E.coli*/100 ml	Turbidity (NTU)
All provinces	3,300	470	2.9	310	14	0.77
Kandal	3000	340	2.8	240	8	0.59
Kampong Chhnang	5,300	940	2.9	360	18	0.77
Pursat	3,000	540	8.4	460	25	1.3

a. Data from intervention households, raw (untreated) water and filtered (treated water) samples from 3 sampling rounds, February-April 2006 (n=203).

Table 5.4. Geometric mean total coliform and *E. coli* counts (cfu/100 ml) and turbidity for samples taken in intervention households (untreated and treated water).

	Percentage[a] of all filter samples by E. coli*, log_{10} reduction values[b] (LRV) (n=203[c])*						
	<0[d]	0[e]	.01-0.99	1-1.99	2-2.99	3-3.99	4.0+
All provinces	17%	10%	12%	16%	36%	7%	2%
Kandal	16%	12%	7%	20%	43%	5%	3%
Kampong Chhnang	19%	10%	12%	7%	40%	10%	2%
Pursat	19%	6%	23%	17%	17%	25%	11%

a. Percentages may not add to 100% due to rounding.
b. Log_{10} reduction values are computed as the $\log_{10}$(effluent/influent); 1 LRV=90% reduction, 2 LRV=99% reduction, 3 LRV=99.9% reduction, and so on. Reduction is a function of influent water, however, and low LRV values do not necessarily indicate poor performance. In forty percent of samples (n=89), filters reduced product water to <1 *E. coli* per 100 ml, so reported LRVs are potential underestimates.
c. 203 (85%) sampling events (out of 240 total: 80 filters sampled three times each) yielded complete data to use in the LRV calculation.
d. Negative LRV values indicate that the effluent water contains more *E. coli* than the influent water.
e. In 100% of these samples the influent water contained 0 *E. coli*/100 ml.

Table 5.5. Summary of $\log_{10}$ reduction values of *E. coli* by CWPs, by province.

Time since implementation (months)	*Number (percentage[a]) of filter samples by* E. coli*, log_{10} reduction values[b] (LRV) (n=203[c]), stratified by time since implementation*						
	<0[d]	0[e]	.01-0.99	1-1.99	2-2.99	3-3.99	4.0+
All (0-48)	35	20	24	32	73	15	4
0-5	8 (23%)	6 (30%)	2 (8%)	4 (13%)	18 (25%)	4 (27%)	1 (25%)
6-11	4 (11%)	1 (5%)	2 (8%)	7 (22%)	7 (10%)	0	0
12-17	0	2 (10%)	1 (4%)	4 (13%)	5 (7%)	0	0
18-23	8 (23%)	5 (25%)	2 (8%)	5 (16%)	14 (19%)	1 (7%)	2 (50%)
24-29	1 (3%)	1 (5%)	3 (13%)	5 (16%)	2 (3%)	1 (7%)	0
30-35	1 (3%)	0	2 (8%)	0	4 (5%)	1 (7%)	0
36-41	5 (14%)	2 (10%)	6 (25%)	4 (13%)	14 (19%)	7 (47%)	1 (25%)
42-48	8 (23%)	3 (15%)	6 (25%)	3 (9%)	9 (12%)	1 (7%)	0

a. Percentages may not add to 100% due to rounding.

b. Log_{10} reduction values are computed as the log_{10}(effluent/influent); 1 LRV=90% reduction, 2 LRV=99% reduction, 3 LRV=99.9% reduction, and so on. Reduction is a function of influent water, however, and low LRV values do not necessarily indicate poor performance. In many cases, filters reduced product water to 0 *E. coli* per 100 ml; here the calculated LRV potentially underestimates performance.

c. Only 203 (85%) sampling events (out of 240 total: 80 filters sampled three times each) yielded complete data to use in the LRV calculation.

d. Negative LRV values indicate that the effluent water contains more *E. coli* than the influent water.

e. In 100% of these samples the influent water contained 0 *E. coli*/100 ml.

Table 5.6. Summary of log_{10} reduction values of *E. coli* by the CWP, stratified by time in use.

	Number (percentage[a]) of filter-treated water samples by E. coli *concentration, stratified by time since implementation*					
Time since implementation (months)	<1 (cfu/100 ml)	1-10 (cfu/100 ml)	11-100 (cfu/100 ml)	101-1000 (cfu/100 ml)	1,000+ (cfu/100 ml)	Total samples[b]
All (0-48)	89	54	38	23	7	211
0-5	22 (25%)	13 (24%)	4 (11%)	4 (17%)	1 (14%)	44
6-11	11 (12%)	5 (9%)	3 (8%)	3 (13%)	0	22
12-17	6 (7%)	2 (4%)	4 (11%)	0	0	12
18-23	16 (18%)	12 (22%)	8 (21%)	3 (13%)	0	39
24-29	4 (5%)	4 (7%)	4 (10%)	2 (9%)	0	14
30-35	4 (5%)	1 (2%)	1 (3%)	2 (9%)	0	8
36-41	15 (17%)	11 (20%)	8 (21%)	5 (22%)	1 (14%)	40
42-48	11 (12%)	6 (11%)	6 (16%)	4 (17%)	5 (71%)	32

a. Percentages within strata may not add up to 100% due to rounding.
b. Incomplete data for 29 (12%) samples.

Table 5.7. Summary of *E. coli* counts (cfu/100 ml) in filter treated water, by time in use.

	Comparison of percentage[a] of filter effluent samples versus stored boiled water samples[b] (control households) by E. coli, *log_{10} reduction values[c] (LRV)*						
	<0[d]	0[e]	.01-0.99	1-1.99	2-2.99	3-3.99	4.0+
CWP	17%	10%	12%	16%	36%	7%	2%
Stored boiled water	13%	7%	5%	21%	40%	11%	2%

a. Percentages may not add to 100% due to rounding.
b. 203 total samples from CWPs, 84 from stored boiled water.
c. Log_{10} reduction values are computed as the log_{10}(effluent/influent); 1 LRV=90% reduction, 2 LRV=99% reduction, 3 LRV=99.9% reduction, and so on. Reduction is a function of influent water, however, and low LRV values do not necessarily indicate poor performance. In many cases, filters reduced product water to 0 *E. coli* per 100 ml; here the calculated LRV potentially underestimates performance.
d. Negative LRV values indicate that the effluent water contains more *E. coli* than the influent water.
e. In 100% of these samples the untreated water contained 0 *E. coli*/100 ml.

Table 5.8. Summary of distribution of log_{10} reduction values of *E. coli* by CWPs compared with boiled, stored water.

Characteristic	Intervention (79 households*)	Control group (80 households)
Number (percent) of households by province		
Kandal	40 (51%)	40 (50%)
Kampong Chhnang	18 (23%)	20 (25%)
Pursat	21 (27%)	20 (25%)
Total number of people in group	528	479
Mean number of individuals per household	6.68	5.98
Number (percent) female	280 (53%)	243 (51%)
Number (percent) children < 5 years of age	77 (15%)	86 (18%)
Number (percent) children 5-15 years of age	143 (27%)	148 (31%)
Formal education level of primary caregiver[a]		
Some or all primary school	19 (24%)	27 (34%)
Some or all secondary school	59 (75%)	52 (65%)
More than secondary	1 (1%)	1 (1%)
Caregiver reported receiving health education[b]		
Yes	23 (29%)	60 (75%)
No	56 (71%)	30 (25%)
Self-reported total household income (US$/month)		
<$50	13 (16%)	19 (24%)
$50-$99	41 (52%)	39 (49%)
$100-$149	15 (19%)	18 (22%)
≥$150	10 (12%)	4 (5%)
Soap observed in household[c]		
Yes	62 (77%)	70 (87%)
No	18 (23%)	10 (13%)
Access to sanitation[d]		
Yes	44 (56%)	35 (44%)
No	35 (44%)	45 (56%)
Caregiver reports washing hands "always"[e]		
Yes	33 (42%)	29 (36%)
No	46 (58%)	51 (64%)
Main drinking water sources during study (dry season)[f]		
Surface water	43 (54%)	48 (60%)
Groundwater	32 (40%)	34 (43%)
Deep well (≥10m)	13 (16%)	12 (15%)
Shallow well	19 (24%)	22 (28%)
Rainwater	6 (8%)	2 (3%)
Safe storage practices observed[g]		
Yes	56 (71%)	50 (63%)
No	23 (29%)	30 (37%)
Observed method of collecting household stored water[h]		
Use hands	35 (44%)	30 (38%)
Pour, tap, or designated dipper	44 (56%)	50 (62%)

*One intervention household was lost to follow up.
a. Usually an adult female who is responsible for child care.
b. Water, health, hygiene, or sanitation education from any source (school, NGO, media, etc).
c. Respondents were asked to demonstrate that soap was present in the household.
d. Shared or own latrine.
e. Caregiver responded that s/he washes hands "always" with soap at critical points such as after defecating.
f. Multiple answers possible.
g. Safe storage was using a covered/narrow mouth water storage container and a designated water dipper to collect water.
h. Respondents were asked to demonstrate their usual method of gathering water from the storage container.

Table 5.9. Selected characteristics of the intervention (households with CWPs) and control (without CWPs) groups from the longitudinal study of water quality and health.

Surveillance Point	*Group*	*Prevalence proportion*	*Unadjusted prevalence proportion ratio*	*Cases*	*Person-days at risk*[a]	*Incidence rate*	*Incidence rate ratio (95% CI)*	*Adjusted PPR (95%CI) by GEE*[b]
1	Control	0.21		98	2947	0.033		
	CWP	0.11	0.55	59	3491	0.017	0.51 (0.36-0.71)	0.55 (0.40-0.76)
2	Control	0.16		75	3079	0.024		
	CWP	0.082	0.52	43	3532	0.012	0.49 (0.34-0.74)	0.52 (0.36-0.75)

a. Cases were assigned a mean duration of 3 days; thus cases received 4 days of at-risk time during each seven day observation period.

b. Prevalence proportion ratio computed via Poisson extension of Generalized Estimating Equations (GEE), adjusted for clustering within households.

Table 5.10. Summary of longitudinal data for diarrheal disease by surveillance point.

	Mean diarrheal disease prevalence proportion over 10 week study period[a]		*Incidence rate ratio*[b] *(95% CI*[c]*)*	*Adjusted prevalence proportion ratio (PPR)*[d] *(95% CI)*
	Intervention	Control		
All persons	0.10	0.18	0.51 (0.40-0.66)	0.54 (0.41-0.71)
Age[e]				
<5 years	0.19	0.37	0.47 (0.29-0.75)	0.52 (0.32-0.86)
5-15 years	0.07	0.10	0.71 (0.38-1.3)	0.72 (0.39-1.3)
≥16 years	0.09	0.16	0.50 (0.35-0.72)	0.52 (0.35-0.76)
Sex				
Male	0.10	0.19	0.48 (0.33-0.69)	0.51 (0.34-0.75)
Female	0.10	0.17	0.55 (0.38-0.78)	0.57 (0.38-0.84)
Province				
Kandal	0.08	0.13	0.62 (0.41-0.92)	0.63 (0.41-0.97)
Kampong Chhnang	0.12	0.18	0.68 (0.41-1.1)	0.70 (0.42-1.2)
Pursat	0.10	0.27	0.34 (0.21-0.54)	0.37 (0.22-0.62)

a. Two sampling rounds, February-April 2006 (dry season). Figures represent the proportion of individuals reporting diarrhea in the previous 7 days.
b. Calculated by assuming a per-case duration of three days. Individuals reporting cases were assigned four days of at-risk time during the seven day follow up period.
c. 95% confidence interval.
d. Adjusted for clustering of diarrheal disease within households and within individuals over time
e. Age in years at the time of the first household visit.

Table 5.11. Diarrheal disease prevalence and filter effect estimates by age and sex of individuals and province.

E. coli*/100 ml in household drinking water*[a]	*Stratum-specific prevalence proportion estimate*	*Prevalence proportion ratio (PPR)*[b]	*95% CI*
<1	0.12	1.0 (referent)	.
1-10	0.10	1.0	0.66-1.7
11-100	0.17	1.0	0.82-1.2
101-1000	0.16	1.1	0.95-1.2
1001+	0.14	0.95	0.84-1.1

a. Households were asked to provide a sample of the water that the family was drinking at the time of visit.
b. Adjusted for clustering within households and for presence of intervention (CWP).

Table 5.12. Stratum-specific outcome estimates for levels of *E. coli* in household drinking water samples.

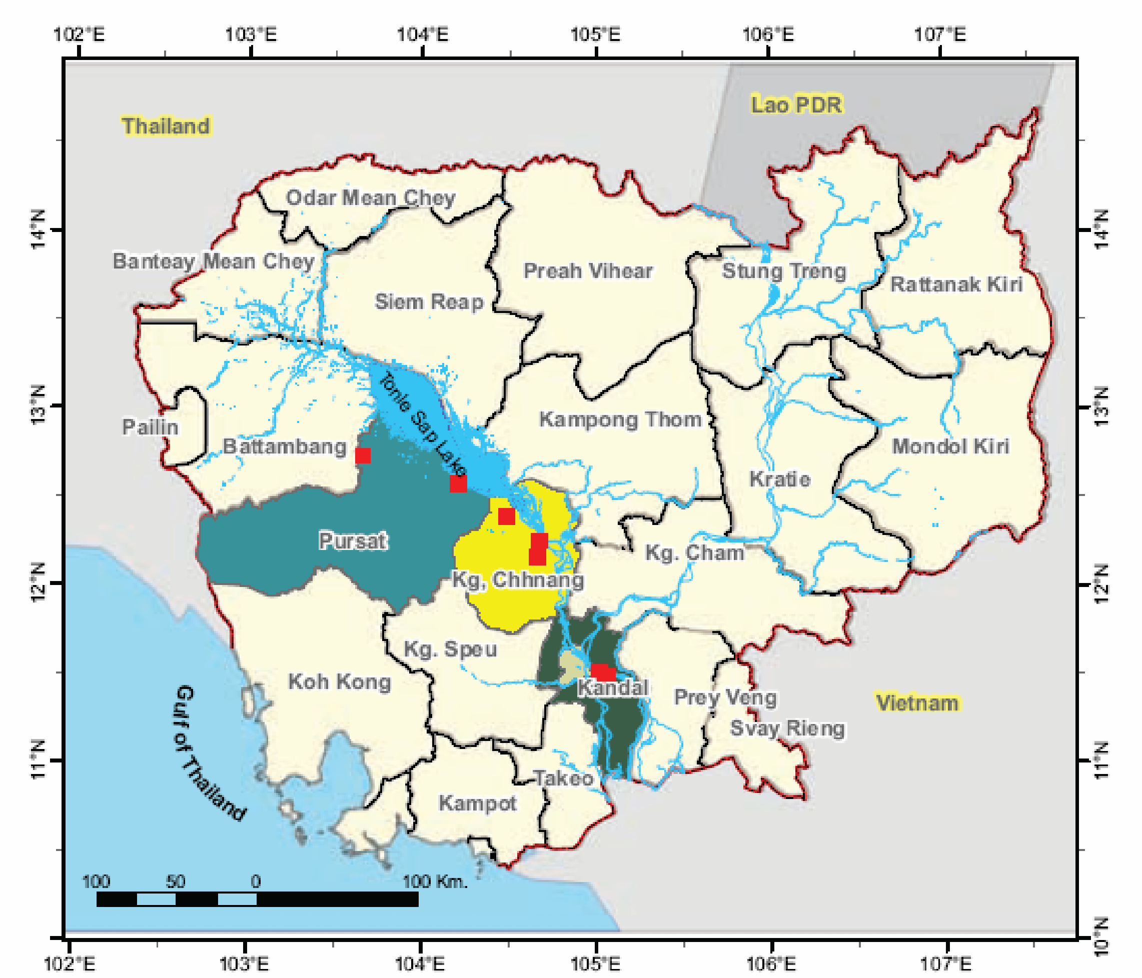

Figure 5.1. Map showing locations of provinces and areas included in the study (red squares) in Cambodia. Study households were taken from 13 rural villages in the provinces of Kandal, Kampong Chhnang, and Pursat. Map credit: Jan-Willem Rosenboom.

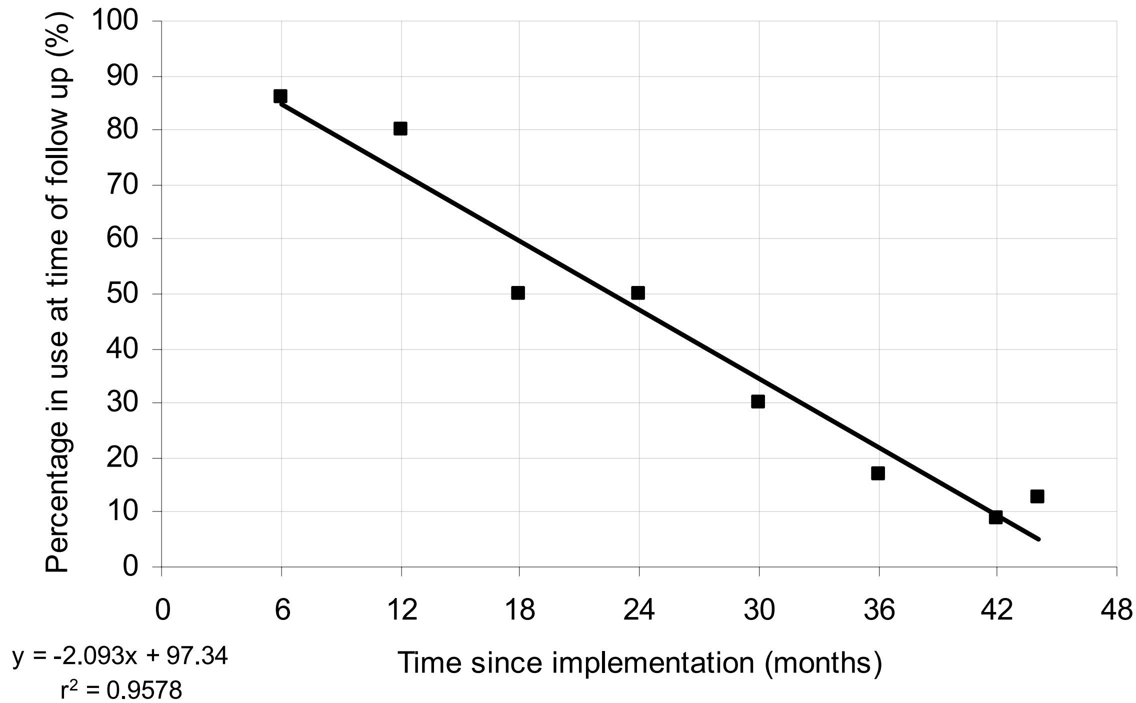

Figure 5.2. Percentage of filters remaining in household use as a function of time, with time as a categorical variable (6 month increments).

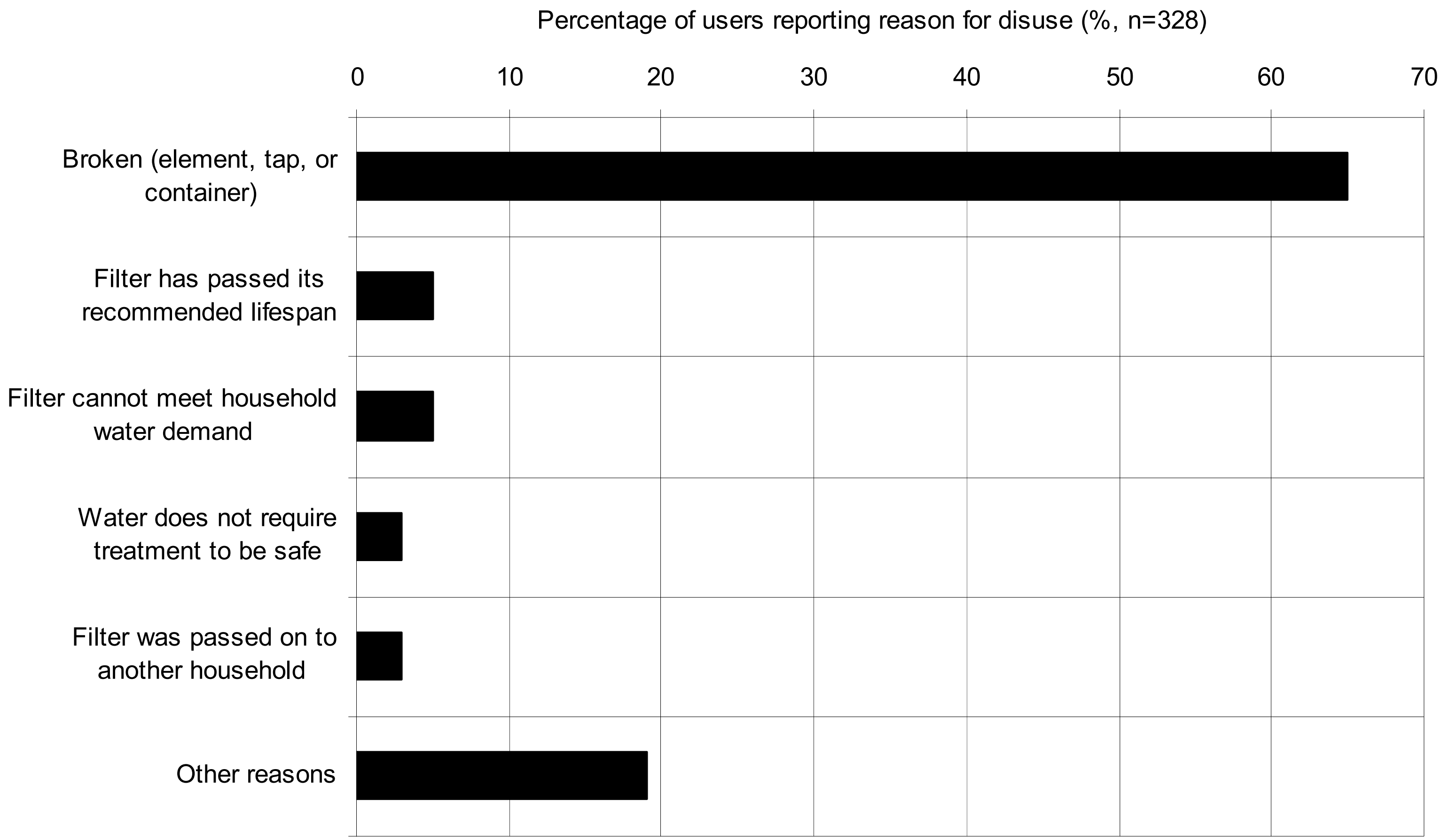

Figure 5.3. Reasons given by respondents for filter disuse at the time of follow up.

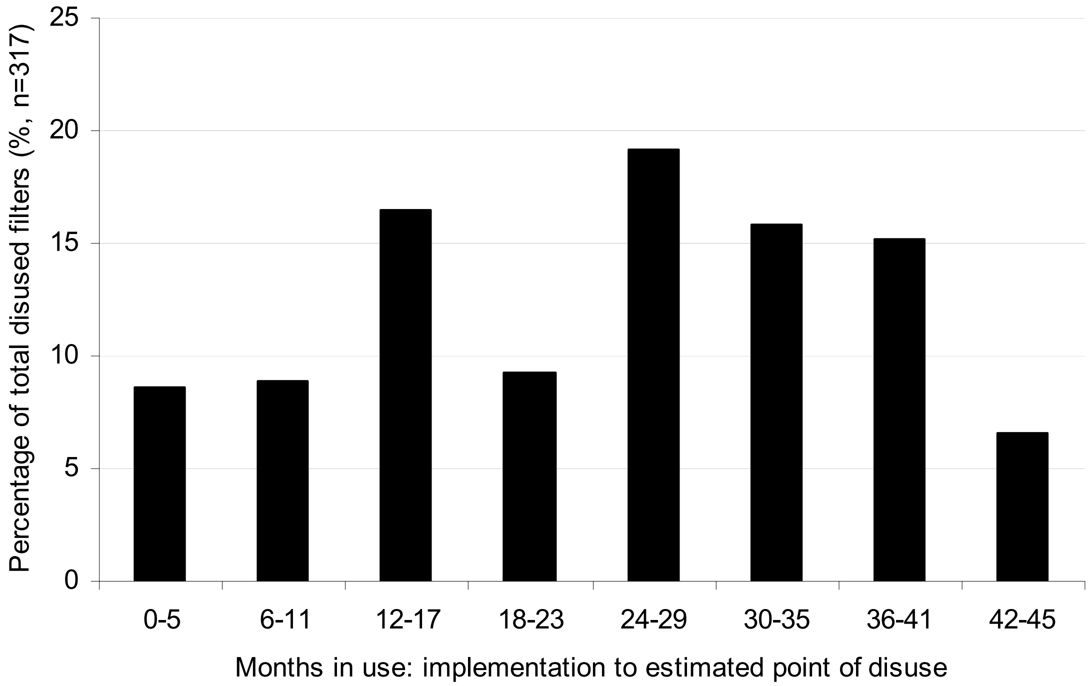

Figure 5.4. Histogram showing the distribution of user-approximated time in use of filters not in use at the time of this follow up study (n=317).

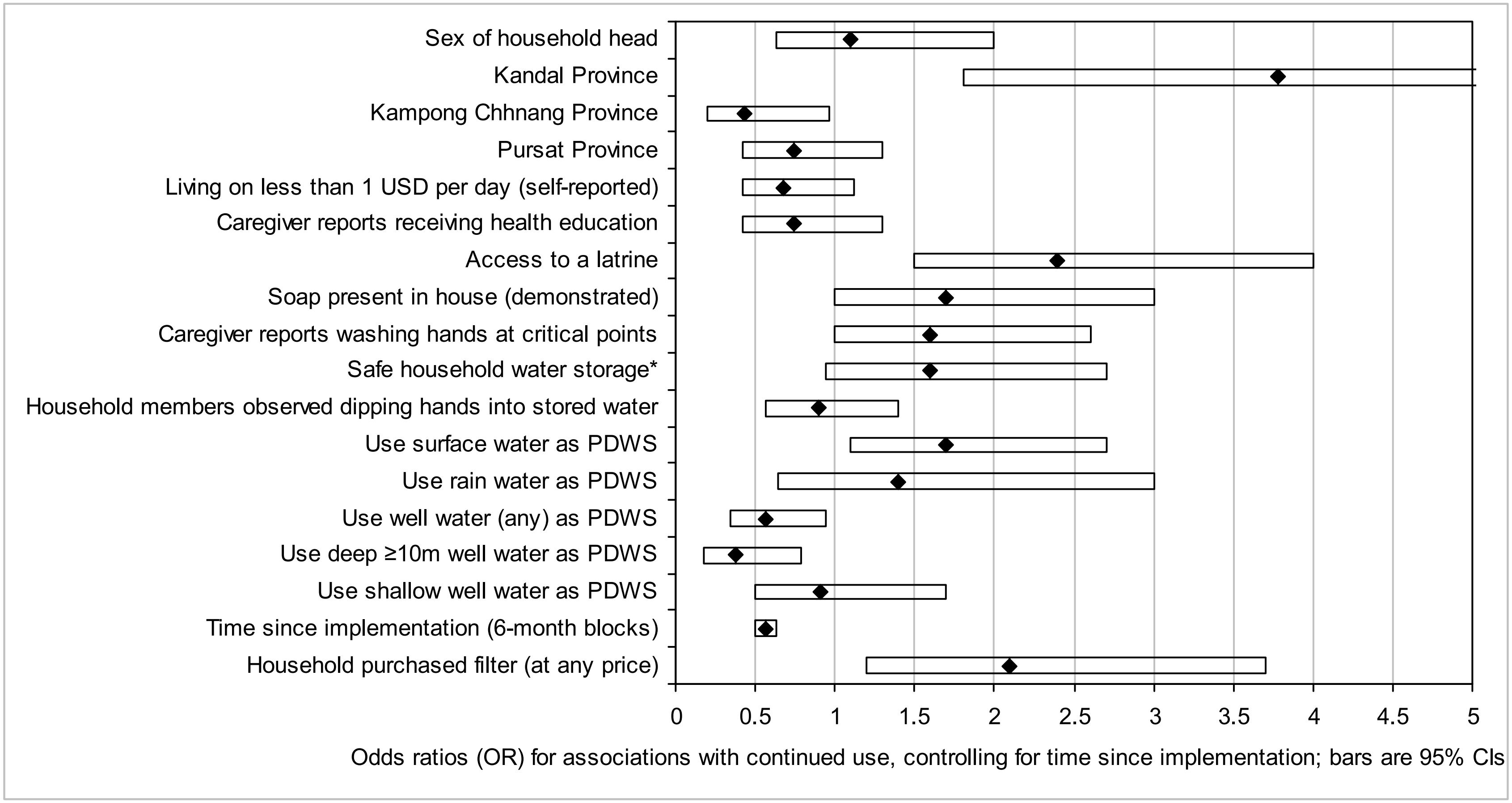

Figure 5.5. Odds ratio (OR) point estimates (and 95% confidence intervals) for factors associated with continued use of the CWP in 506 households in Kandal, Kampong Chhnang, and Pursat Provinces, adjusted for time since implementation. Odds ratios less than one are negatively associated with continued use and odds ratios greater than one are positively associated with continued use.
PDWS = Primary drinking water source (non-exclusive); * Covered household water storage container observed

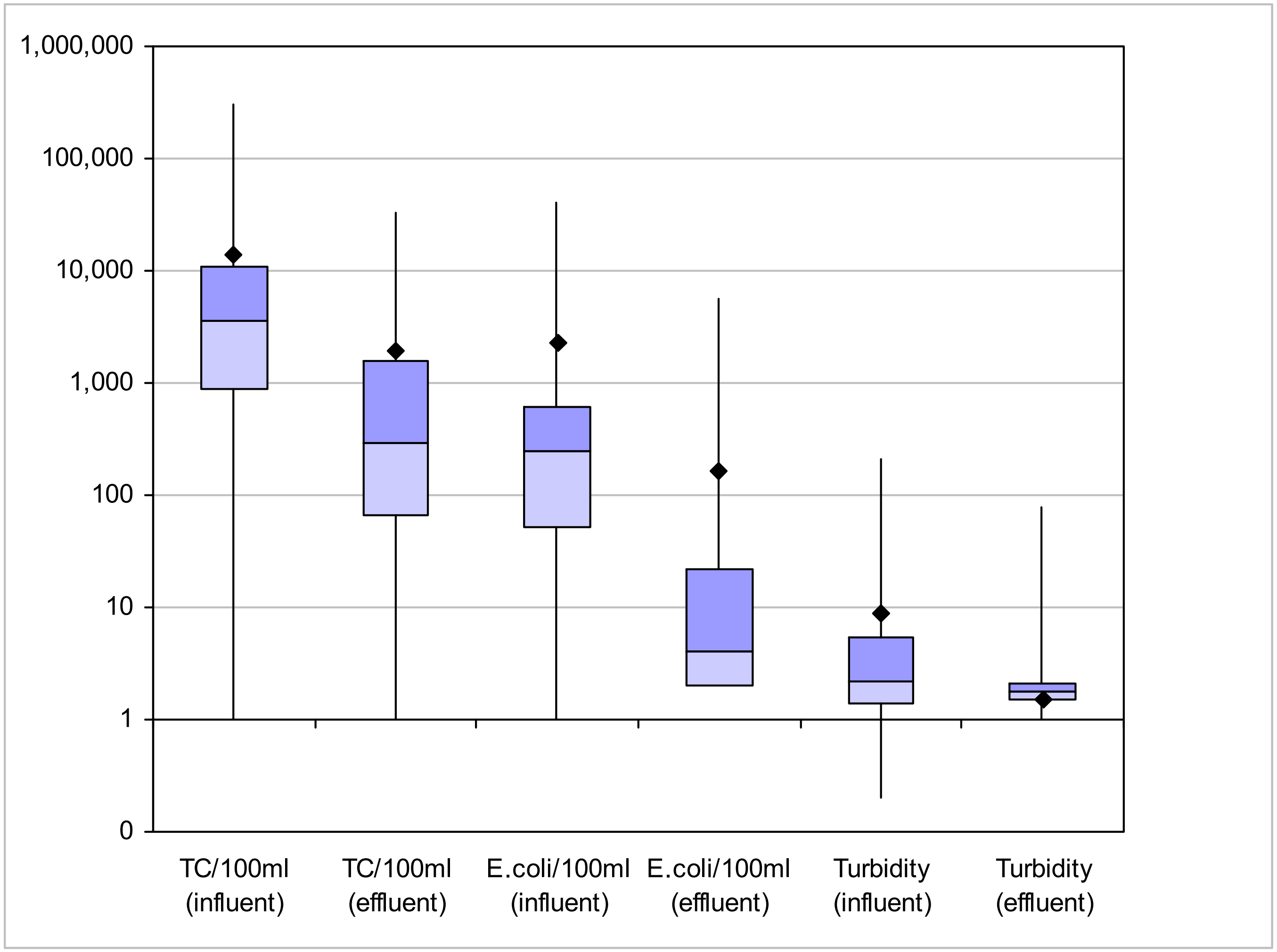

Figure 5.6. Box-and-whisker plot showing data for total coliform, *E. coli*, and turbidity (measured in NTU) in all filter influent and effluent samples. Upper and lower points represent maxima and minima, boxes indicate 25th and 75th percentile boundaries, the color break within each box represents the median value, and the points are arithmetic means (note log scale).

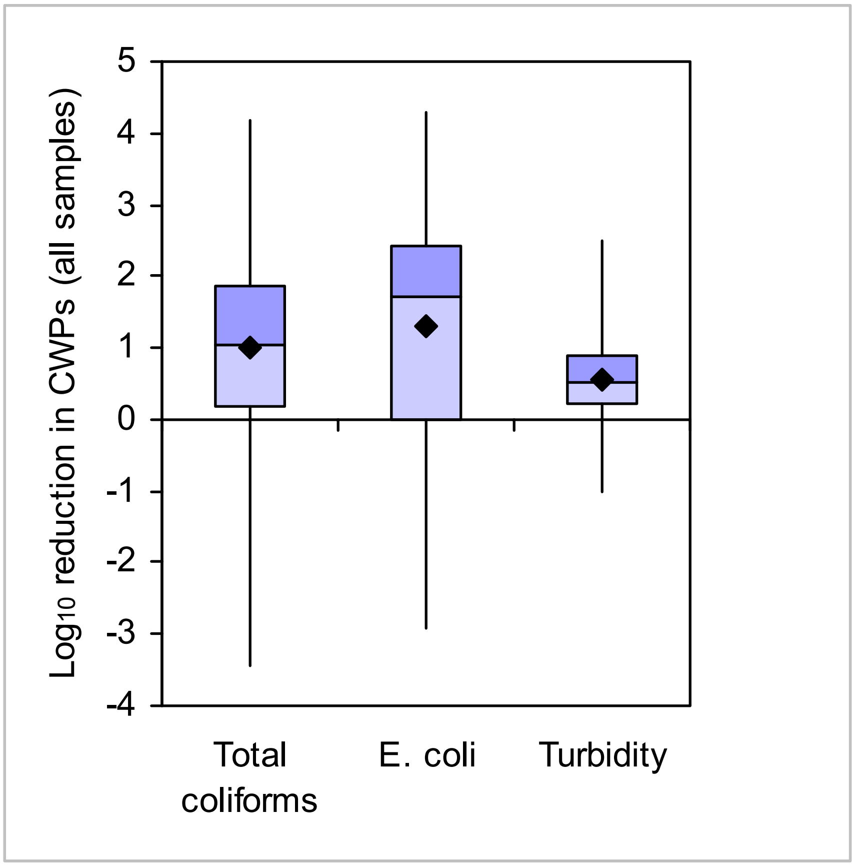

Figure 5.7. Box-and-whisker plot showing $\log_{10}$ reductions for total coliform, *E. coli*, and turbidity in the CWP. Upper and lower points represent maxima and minima, boxes indicate 25^{th} and 75^{th} percentile boundaries, the color break within each box represents the median value, and the points are arithmetic means

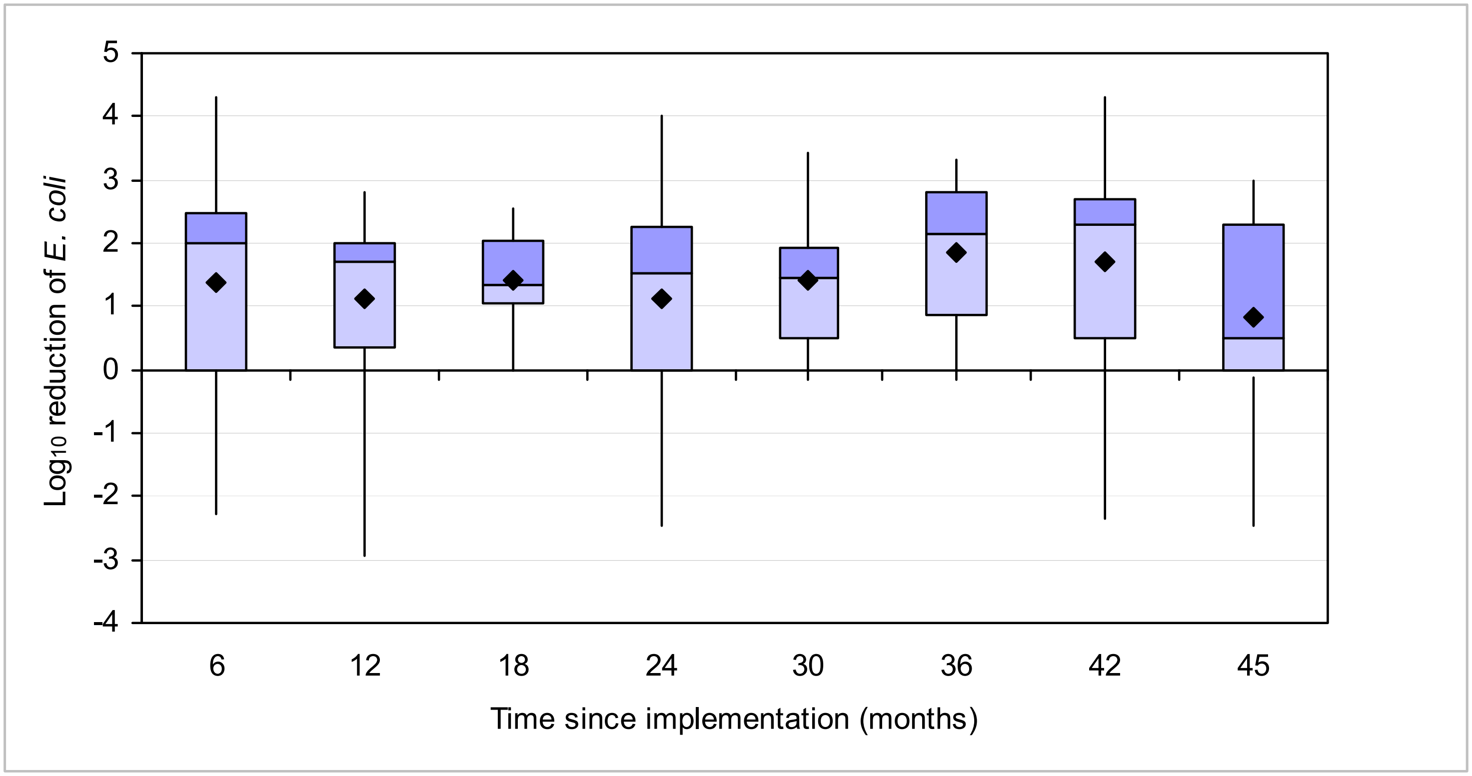

Figure 5.8. Box-and-whisker plot for $\log_{10}$ reduction of *E. coli* in all treated versus untreated water samples by time since implementation, coded in 6-month blocks. Upper and lower points represent maxima and minima, boxes indicate 25^{th} and 75^{th} percentile boundaries, the color break within each box represents the median value, and the points are arithmetic means.

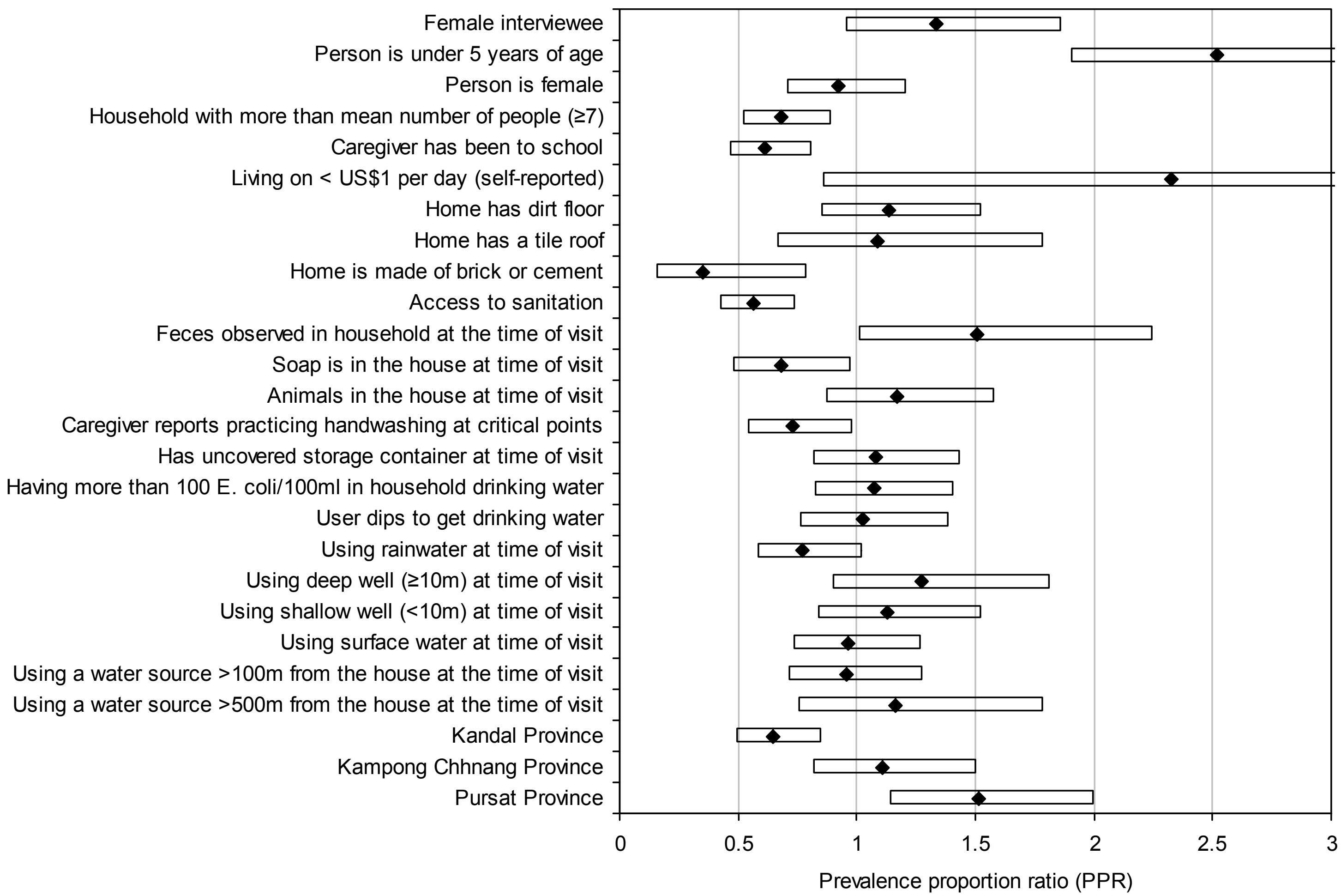

Figure 5.9. Association of measured covariates with diarrheal disease in all individuals, adjusted for presence of the intervention (CWP) and for clustering of the outcome within households and in individuals over time. Points are arithmetic means and bars represent 95% confidence intervals.

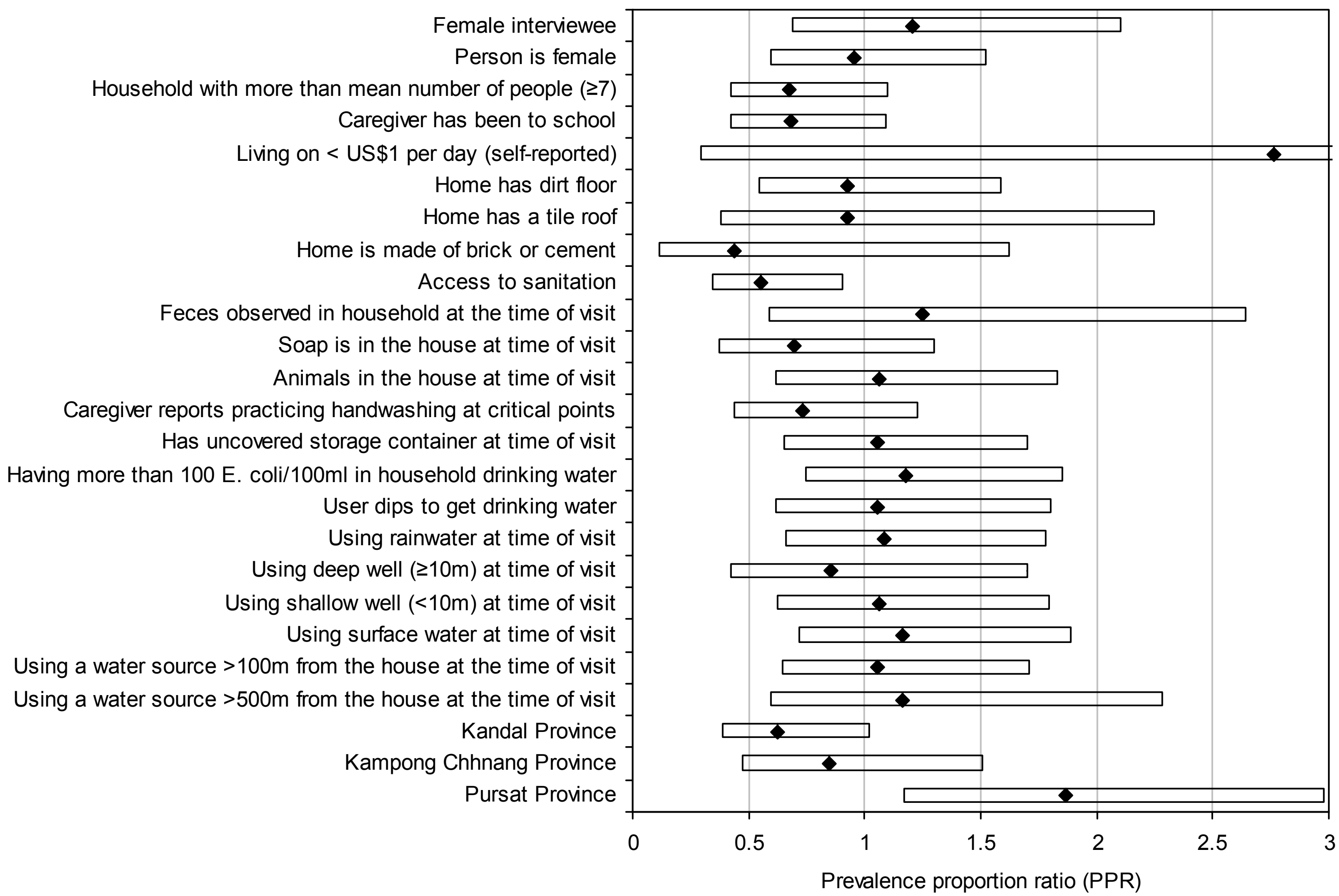

Figure 5.10. Association of measured covariates with diarrheal disease in children under five years of age (0 – 48 months at first household visit), adjusted for presence of the intervention (CWP) and clustering within households and in individuals over time. Points are arithmetic means and bars represent 95% confidence intervals.

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CHAPTER 6: SUMMARY, CONCLUSIONS, AND FUTURE WORK

6.1 Summary

Despite widespread and increasing international attention given household-scale water quality interventions, basic gaps in knowledge of the microbiological effectiveness and associated health impacts of the technologies limit investment in this method increasing access to safe water. Point-of-use water treatment technologies require a sound base of evidence resulting from systematic, rigorous laboratory and field testing before they are promoted widely as public health interventions.

This dissertation contributes to the current knowledge of the potential role of locally produced ceramic water filters in improving household drinking water quality and reducing diarrheal disease. These studies are the first to: (i) rigorously evaluate the microbiological performance of low-cost ceramic filters in the laboratory and in the field, over extended use periods and against a range of environmental waters; (ii) assess the impact of the filters on diarrheal disease outcomes in a randomized, controlled trial and a prospective cohort study; and (iii) examine the continued use and effectiveness of the filters after up to 44 months in field use. This post-implementation assessment has been the first systematic evaluation of any household water treatment intervention after long-term field use.

The filter's demonstrated effectiveness in improving water quality and health compares favorably with other proposed point-of-use water quality interventions (Clasen *et al.* 2007). Specific findings are articulated below.

6.2 Conclusions

6.2.1 Microbiological performance: laboratory and field testing (Chapter 3)

- The CWP1 and CWP2 significantly reduced surrogates for waterborne bacterial and viral pathogens, with a mean of approximately 99% (2 log_{10}) reduction for *E. coli* bacteria (laboratory and field testing) and 90-99% (1 - 2 log_{10}) reduction for viruses (laboratory testing only).
- Laboratory and field reduction of *E. coli* by filters were comparable.
- Reduction of *E. coli* was greater in the CWP1 filter, followed by the CWP2 and CWP3 filters in laboratory testing.
- The CWP1 reduced *E. coli* in field testing to a marginally greater extent than did the CWP2.
- The reduction of MS2 in laboratory testing was not significantly different between filters.
- The application of silver compounds to CWP-type filters is widely held to increase microbiological effectiveness but this was not observed in this study. The CWP3, having no application of silver, was observed to be comparable in microbiological effectiveness to the CWP1 and CWP2 (with silver amendment).
- The addition of iron oxide amendments to the base clay before firing (CWP2) did not significantly change the microbiological effectiveness of the filters in the laboratory or in the field against *E. coli* or MS2.
- Effectiveness of filters against the bacterial indicator *E. coli* was maintained during field use conditions over 18 weeks, although statistically significant changes in mean reductions over the sample period were observed.

- Log_{10} reductions of *E. coli* in boiled water samples were comparable to performance of the filters over the 18 week field trial. This finding suggests that boiled water may be recontaminated after treatment through improper storage.
- Reduction of indicators was marginally higher in more turbid waters, both in the laboratory and in the field, probably due to either particle association of microbes or higher levels of *E. coli* in field samples with higher turbidity.

6.2.2 Health impacts from a randomized, controlled trial (Chapter 4)

- The use of either filter resulted in a marked decrease in diarrheal disease during the study (49% reduction over the control group by use of the CWP1, 42% reduction by use of the CWP2), an effect that was observed in all age groups and both sexes after controlling for clustering within households and within individuals over time.
- The CWP1 filter was associated with a substantial reduction in dysentery (61%), an effect that was not observed with the CWP2.
- There was a positive but weak association between *E. coli* levels measured in drinking water and diarrheal disease outcomes, after controlling for presence of the intervention.

6.2.3 Continued use and effectiveness (Chapter 5)

- The rate of filter disuse was approximately 2% per month after implementation, due largely to breakages. There was a strong association between filter use and time since implementation.

- Controlling for time since implementation, continued filter use over time was most closely positively associated with related water, sanitation, and hygiene practices in the home, cash investment in the technology by the household, and use of surface water as a primary drinking water source. Continued use of the filters was associated with awareness of other water, sanitation, and hygiene behaviors and improvements, suggesting possible synergies between CWP implementation and successful long-term use by users.
- Although continued use of the filters was positively associated with cash investment, continued use was not observed to be closely related to the price paid.
- The filters reduced *E. coli*/100 ml counts by a mean 98% in treated versus untreated household water, although demonstrated filter field performance in some cases exceeded 99.99%.
- Microbiological effectiveness of the filters was not observed to be closely related to time in use. Since time in use was not shown to be strongly related to performance, recommendations that users replace the ceramic filter elements every one or two years (as is current practice) may not be necessary.
- The filters can be highly effective in reducing microbial indicator organisms but may be subject to recontamination, probably during "cleaning" with soiled cloths; Recontamination of the filter and storage receptacle through improper handling practices is a real threat to the effectiveness of this technology.
- The filters were associated with an estimated 46% reduction in diarrhea in filter users versus non users (PPR: 0.54, 95% CI 0.41-0.71).

- No association was observed between measured *E. coli* in household drinking water and diarrheal disease, after adjusting for presence of the intervention and clustering within households.
- Other significant associations were observed with water, sanitation, and hygiene-related factors that were also measured as part of the study, such as handwashing, maternal education, measures of socio-economic status, and access to sanitation, after adjusting for the presence of the intervention and for clustering of outcomes within households and in individuals over time.

6.3 Research needs and remaining questions

The production of ceramic water filtration devices at the local level in developing countries is made possible by the fact that the necessary materials and knowledge are widely available and relatively inexpensive, although adapting these to the production of a high quality, low-cost, economic and socially sustainable, and proven device to provide safe water and reduce diarrheal disease does require significant innovation and investment. Despite widespread and increasing international attention given household-scale water quality interventions, basic gaps in knowledge of the microbiological effectiveness and associated health impacts of technologies limit investment in this method for safe water provision. More basic research on technologies is needed for these interventions to play a major role in providing safe water to the billions of people lacking it (Thompson *et al.* 2003). Scaling up the manufacture and distribution of the filters to households requires a base of evidence from well-designed studies to determine: (i) the microbiological effectiveness of the technology against human pathogens and indicators, including application of Environmental Technology Verification (ETV) protocols where possible and appropriate; (ii) the health impacts associated with using the technology, as assessed using appropriate rigorous epidemiological methods, including blinded, randomized controlled trials; and (iii) appropriate and effective large-scale implementation strategies to ensure high quality filters are produced within an economically sustainable program, resulting in long-term and widespread availability of new filters, replacements, parts, and facilitating and supporting expertise. These points for further research are articulated below.

6.3.1 Microbiological effectiveness

More research is needed on the microbiological effectiveness of the CWPs both in the laboratory and in the field. Although filters performed well based on two bacterial indicators in this study, the performance of the filters in reducing viruses, protozoan parasites, and potentially important bacterial pathogens has not been adequately characterized. Evidence suggests that filter effectiveness may be improved through systematic testing and optimization of key parameters, such as: pore size, flow rate, base clay, burnout material, and microbiocidal surface treatments or additives. Because each manufacturer of CWPs in Cambodia and worldwide uses different materials and QA/QC procedures, effectiveness is also likely to vary, potentially considerably (Van Halem 2006). Each CWP program will thus need to perform adequate testing of filters before field implementation to ensure users are protected. Although standardized protocols for microbiological testing of household-scale water treatment devices do exist and are applied in wealthy countries (e.g., USEPA 1987; NSF 2002), these have not been widely used in developing countries due to resource limitations and other reasons. There is a WHO-led effort now to introduce flexible, standardized criteria for water treatment technology testing with specific application in developing countries and in harmony with the WHO risk-based framework for drinking water quality as articulated in the *Guidelines for Drinking Water Quality*, 3rd Ed. (WHO 2006). Such protocols, combined with new and less expensive water testing procedures for indicators (e.g., Love and Sobsey 2007; Mattelet 2005), will enable performance verification by users, implementers, and regulators in resource-limited settings.

6.3.2 Health impacts

More research is needed on the health impacts of the CWPs. Specifically, randomized, controlled, blinded intervention trials should be performed in order to assess the effectiveness of the CWPs in reducing diarrheal diseases. The studies described here may be subject to reporting bias and selection bias, which can be further minimized through appropriately-designed trials that include a placebo filter and randomized treatment arms. Because health impacts may vary from population to population, several studies may be needed to adequately characterize the effectiveness of the intervention on diarrheal and other waterborne diseases among users.

6.3.3 Scaling up

More research is needed on appropriate scale-up strategies that will increase coverage of water quality interventions to reduce the burden of disease in developing countries. A better understanding of the socio-cultural, economic, and practical limitations to use of technologies is critical. Methods for achieving positive behavior change through marketing and education may be highly context-specific. Local research is necessary before or concurrent with the inception of household water treatment intervention programs. Appropriate and effective implementation strategies can help ensure high quality filters are produced within an economically sustainable program, resulting in long-term and widespread availability of new filters, replacements, parts, and facilitating and supporting expertise.

6.3.4 Long-term follow up to assess sustainability

This dissertation describes one long-term follow up study of locally produced ceramic filters in field use (Chapter 5). Point-of-use water treatment and safe storage interventions can greatly benefit from such systematic post-project appraisals (PPAs) to determine successes, failures, and challenges that will inform current and future efforts. To date, no standard method has been used by implementers of household water treatment. Unfortunately, looking back at previous projects to assess performance has not been a priority in the water and sanitation sector, perhaps as the problems of safe water and sanitation access are so urgent the focus remains, justifiably, on new interventions and expansion of programs. While increasing coverage of interventions is important in increasing global access to safe water, critical program evaluation can ensure that interventions are working to protect users from waterborne disease.

Good PPAs use standard or other easily interpretable measures for purposes of comparison and include a representative sample from the target population. They may also be led by an entity independent of the implementer, which can make the study more objective for the organization and potentially more credible to outside observers. For POU water quality interventions, objective PPAs should assess water quality improvements at critical points between the source water and consumption, health impacts at the household and population level, and sustainability of the intervention through measurable uptake and use rates and in relation to economic, environmental, and socio-cultural criteria.

6.4 References

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