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User Compliance, Field Efficacy, and Greenhouse Gas Emissions of an Ultraviolet Water Disinfection System and other Drinking Water Treatment Alternatives for Rural Households in Mexico

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by

Fermín Reygadas Robles Gil

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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in

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Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Isha Ray, Co-chair
Professor Kara L. Nelson, Co-chair
Professor John M. Colford Jr.

Fall 2014

User Compliance, Field Efficacy, and Greenhouse Gas Emissions of an Ultraviolet Water Disinfection System and other Drinking Water Treatment Alternatives for Rural Households in Mexico

Abstract

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Fermín Reygadas Robles Gil

Doctor of Philosophy in Energy and Resources

University of California Berkeley

Professors Isha Ray and Kara L. Nelson, Co-chairs

Many households in developing countries rely on contaminated and untreated drinking water sources, contributing to gastrointestinal illness and other health risks. Even piped water quality is often unreliable because of poorly-maintained treatment or distribution systems. Household water treatment (HWT) systems aim to enable users to treat their water at the point of use, making it safe to drink. While some HWT options have been successful in improving health in developing countries, low adoption and sustained use outside pilot projects and epidemiological trials remains one of the current challenges with this approach. Furthermore, Quantitative Microbiological Risk Assessment models predict that the health benefits from water quality interventions drop significantly with even occasional consumption of contaminated water. Therefore, to be effective, HWT options need to achieve high user compliance rates and provide safe water reliably.

I begin my thesis with an interdisciplinary analysis of the field of water, health, and development, followed by a description of my research study site. Using an interdisciplinary research approach, grounded in the local context, I led the development of an ultraviolet (UV) water disinfection system for rural households. This included an iterative process of design and field tests to create a user-friendly system and laboratory research to improve the performance of the technology. I also collaborated with a non-profit organization based in Mexico in the design of an implementation program to support the adoption and consistent use of the UV system.

Then I present the design and application of a stepped-wedge cluster randomized trial in rural Mexico to evaluate compliance with the implementation program and field efficacy of the UV system. I developed a framework that disaggregates and measures the components of compliance from initial adoption of a safe water practice to exclusive consumption of safe water. I applied this framework to measure compliance across intervention and control groups and to test if additional program components that improve convenience to users can be a cost-effective approach to increase compliance. I present evidence that the implementation program significantly improved compliance with the habit of consuming safe water, when compared to the practice of purchasing water bottled in reusable 20 L containers in the control group. The

additional program components proved to be a cost-effective strategy to increase compliance immediately post-intervention, but their impact degraded with time. By analyzing results across different compliance components, I find limitations of the current HWT approach. I present the rational for pilot testing strategies outside the current HWT paradigm, such as expanding a narrow focus on drinking water to making all domestic water safe to drink (as suggested by our observations of multiple water access points in the household) or switching from a product-based to a service delivery model.

As a second component of the randomized trial, I present a series of controlled comparisons to evaluate the field efficacy of the UV system using *E. coli* as a fecal contamination indicator in drinking water. I use an as-treated-analysis to isolate the impact of the system and contrast these results with an impact evaluation of the implementation program led by a research colleague. I also created a drinking water reliability framework to compare potential contamination impacts from different household water management practices and a logistic regression model to assess household risk factors for post-UV-treatment contamination. I show that treating water with the UV system and storing it in 20 L narrow-necked containers, allowed households to significantly improve their drinking water quality and gain access to a more reliable source of safe water. However, I also found evidence of post-treatment contamination. Through the logistic regression model, I identify that inexperienced system operators, poor household infrastructure, and pouring water in drinking glass are associated with increased risks of contamination. Considering the current unviability of monitoring water quality in real time, the reliability framework proved to be a useful tool to generate a more realistic representation of the variations in water quality that households are exposed to. The processed-based model was also useful in identifying areas that can be targeted by HWT programs to improve water quality outcomes.

In the final chapter I investigate the greenhouse gas (GHG) emissions associated with the use of HWT technologies in Mexico. I do that by carrying out a literature review of existing studies assessing energy use of water treatment technologies; using secondary data to perform a life cycle assessment (LCA) capturing the embedded CO_2 equivalent emissions of individual HWT products; and developing model to calculate a metric of GHG emissions per volume of water used (kg CO_2 eq/m^3) representative of the HWT sector in Mexico. Filtration, ozone, and UV disinfection technologies resulted in similar LCA emissions, while reverse osmosis had emissions five times higher than the average of the rest. I also find GHG emissions of HWT to be 30 times lower than water bottled in 20 L reusable containers. In a context in which mortgage institutions have created green credit mechanisms, this result is useful for expanding financing options for HWT products, which are often more cost-effective than bottled water, but require a higher capital investment.

I dedicate my Ph.D. research and development work to my wife, for her love, support, patience, sacrifice, and leadership throughout this endeavor.

I file this dissertation:

> with great gratitude to my parents, for bringing me to life and giving me a compass to navigate it;
>
> as a commitment to continue working with rural communities in the development of safe water solutions and healthier livelihoods; and
>
> in memory of the 100,043 people that were killed or disappeared in my home country during the time I studied my Ph.D., partly as a consequence of flawed policies, leadership failure, and civic disengagement in Mexico and the United States of America.
> May the remembrance of their lives help us put an end to this ongoing injustice and guide us in the construction of a better society.

"Solo pido…
que el dolor no me sea indiferente,
y que la reseca muerte no me encuentre
vacío y solo sin haber hecho lo suficiente."

("I only ask…
that I don't become indifferent to pain,
and that the dry death won't find me
alone and empty without having done enough.")

- Adapted from León Gieco

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Jack Colford has been a very important advisor for me and my research. Through his classes I learned about the importance of rigorous designs in health research. These principles became crucial for my dissertation and continue to inform the work that we do in Cantaro Azul. I am grateful for the many opportunities he has opened for me and he will always remain an important mentor in my work.

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I appreciate all of the feedback and constructive criticism I received from members of the ERG Water Group and many other Berkeley water colleagues, including Ben Arnold, Khalid Kadir, Emily Kumpel, and Rebecca Peters. I look forward to continue collaborating and learning from each other in the years to come.

I want to thank the students, faculty, and staff at the Energy and Resources Group. It has been an amazing and very enriching experience to be part of this community. I want to thank: Daniel Kammen for his early support in the UV Tube project and Cántaro Azul, and for offering me the great opportunity to serve as graduate student instructor of Energy and Society; Kay Burns for her always kind support; and Zach Burt for helping me in key moments, including his support in the Community Driven Development course and the timely submission of my dissertation paperwork!

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Chapter 1. Introduction

1. GLOBAL HEALTH IMPACT OF GASTROINTESTINAL ILLNESS

Gastrointestinal (GI) illness constitutes the second largest cause of global burden of disease in disability-adjusted life years (DALYs) and is estimated to be responsible for over 4 billion cases of diarrhea and 2 million deaths each year (WHO 2008). Apart from the direct impact on mortality and morbidity, repeated diarrhea and nematode infections cause approximately 50% of the malnutrition in children under the age of 5 years, leading to an additional 860,000 annual deaths (Prüss-Üstün et al. 2008) and an impairment in the growth, cognitive development, and school performance of those that survive (Guerrant et al. 2002).

GI illness falls disproportionally on the youngest and those who have fewest resources to cope with it. Approximately 70% of the deaths and 75% of DALYs associated with diarrhea occur in children under the age of 15 living in low-income countries, who only represent 14% of the global population. The annual mortality rate associated with diarrheal diseases in children under the age of 15 in low-income countries is 120 times higher than in high-income countries (WHO 2008). Although diarrhea-related mortality in low-income countries has recently decreased (at an unacceptably slow rate), morbidity has remained fairly constant (Kosek et al. 2003). Such stark contrast between economically rich and poor regions, together with the dramatic reduction in GI illness and deaths observed in high-income countries during the first half of the 20th century (Armstrong et al. 1999; McKeown et al. 1975; Omran 2005) and in middle-income countries over the past 30 years (Kosek et al. 2003), indicates that the great majority of current mortality and morbidity cases are preventable.

2. INTERVENTIONS TO REDUCE GASTROINTESTINAL ILLNESS

GI diseases are caused by various types of pathogenic viruses, bacteria, protozoa, and helminths that produce a variety of health effects and that have diverse hosts, reservoirs, transmission modes, susceptibilities to control mechanisms, and infectious doses. Due to the wide range of disease-causing pathogens, multiple transmission pathways, and interactions with other health conditions, tackling the root causes of GI illness requires a combination of environmental, educational, behavioral, technological, nutritional, and medical interventions. Furthermore, the great cultural, economic, institutional, and ecological diversity across different regions of the world is likely to modulate the effectiveness of specific interventions. Thus, an extensive repertoire of interventions and information about their effectiveness in different settings can be a crucial tool in addressing the global challenge of GI illness.

Medical treatment and case management programs can be effective in controlling the progression of GI diseases in individuals, but are not as effective in limiting their spread in the population and do not address the health complications that arise from relapse and persistent diarrhea (Bartram and Cairncross 2010). Oral rehydration therapy has had an important contribution to the reduction of diarrhea-related mortality by preventing severe dehydration (Victora et al. 2000). Certain anti-diarrheal compounds, such as bismuth, zinc, and lactobacillus, have been shown to be helpful in reducing symptoms in specific situations (particularly in combination with oral rehydration therapy), while others may have no proven effect or even cause adverse effects. Antibiotic treatment can be highly effective for treating *Shigella*, *enterotoxic E. coli*, and *V. cholera*, but its general use in treating GI illness is not recommended because of the risk of increasing the antibiotic resistance of enteric pathogens (Canadian Paediatric Society 2003), which can be especially problematic in developing countries where misidentification of disease is common due to the lack of laboratory analysis to confirm clinical diagnosis. Anti-parasitic drugs are effective for most intestinal protozoa and helminths (Pérez-Molina et al. 2010). Additionally, for certain parasites, treatment of some individuals can lead to a disease reduction in their larger community (Bundy et al. 2009). Two recently developed rotavirus vaccines also hold a promise in reducing diarrhea-related morbidity and mortality. They proved to be effective in quite large initial epidemiological trials, but they still face financial and programmatic challenges, in addition to questions of their immunity duration and adverse effects in older children (Glass et al. 2006).

3. WASH INTERVENTIONS

Measures that target pathogens and their transmission pathways directly, such as securing reliable access to water in sufficient quantities, consuming safe drinking water, using improved sanitation facilities, and adopting adequate hygiene practices, play a critical role in reducing the exposure to GI illness and the spread of disease, thereby impacting both morbidity and mortality. Current evidence from several epidemiological studies shows that water, sanitation, and hygiene (WASH) interventions prevent, on average, one third of diarrheal disease (Fewtrell et al. 2005). Furthermore, such epidemiological studies were carried out in a wide range of settings and over an extended period of time, which indicates a consistent and robust effect. However, even when these services are widely considered to be essential to life[1], adequate water, sanitation, and hygiene conditions are partly or fully absent in many regions of the world. In 2010, the WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation reported that 884 million people do not use improved sources of drinking-water and 2.6 billion people do not use improved sanitation (WHO and UNICEF 2010). Although these are already unacceptably high numbers, hundreds of millions more are at risk from drinking water from systems with unreliable quality and from using sanitation facilities without hand-hygiene stations.

There is significant debate and tension in the literature and practice, often motivated by economic limitations, surrounding which WASH interventions, if any, should be prioritized. To inform such discussions, it is important to consider how each type of WASH intervention works to protect the public health and how each meets other non-health related needs of the end user.

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[1] *Examples of this consensus are:*

- *The UN Millennium Development Goal 7c, which seeks to "Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation", using 1990 as baseline* (WHO and UNICEF 2010).
- *The United Nations General Assembly declaration (July 28th 2010) of safe drinking water and sanitation as a human right essential to the full enjoyment of life and all other human rights. Followed by the United Nations Human Rights Council affirmation that the right to water and sanitation is contained in existing human rights treaties, and that States have the primary responsibility to ensure the full realization of this and all other basic human rights* (United Nations News Service Section 2010).

Table 1.1: Classification of WASH-related infectious diseases (Cairncross and Feachem 1993)

Fecal-Oral (Water-Borne, Water-Washed, Insect Vector)	
Diarrheas and dysenteries	
Rotavirus diarrhea	Virus
Pathogenic *E. coli*	Bacterium
Amoebic dysentery	Protozoon
Campylobacter enteritis	Bacterium
Cholera	Bacterium
Cryptosporidiosis	Protozoon
Giardiasis	Protozoon
Salmonellosis	Bacterium
Shigellosis	Bacterium
Balantidiasis	Protozoon
Enteric fevers	
Typhoid	Bacterium
Paratyphoid	Bacterium
Poliomyelitis	Virus
Hepatitis A	Virus
Leptospirosis	Spirochaete

Strictly Water-Washed	
Infectious skin diseases	Multiple
Infectious eye diseases	Multiple
Louse-borne typhus	Spirochaete
Louse-borne relapsing fever	Rickettsia
Water-Based	
Schistosomiasis	Helminth
Guinea worm	Helminth
Fascilopsiasis	Helminth
Colonorchiasis	Helminth
Diphyllobothriasis	Helminth
Soil-Based and Field-Based	
Ascariasis	Helminth
Trichuriasis	Helminth
Hookworm	Helminth
Taeniasis	Helminth

WASH interventions reduce the risk of illness by disrupting or blocking the transmission pathways of pathogens through different mechanisms and at different phases of their infection routes (Bartram and Cairncross 2010; Cairncross and Feachem 1993):

- **Water treatment** interventions remove or inactivate water-borne and fecal-oral pathogens, as well as certain water-based helminths, before human consumption occurs.
- **Water distribution** interventions increase the availability of water and thus enable more frequent and adequate hygienic practices such as handwashing, bathing, and household cleaning, which in turn reduce the transmission of fecal-oral pathogens, skin and eye infections, and diseases carried by arthropods.
- **Hygiene** interventions seek to motivate the target population to adopt more frequent and adequate hygienic practices to reduce the transmission of fecal-oral pathogens, skin and eye infections, and diseases carried by arthropods.
- **Sanitation** interventions isolate human excreta to limit the spread of water-borne, fecal-oral, and water-based pathogens via water bodies; soil-helminths and tapeworms via soil and agricultural fields; and fecal-oral pathogens via hands, fomites (inanimate objects), and insect vectors.

Due to the existence of many types of pathogens and transmission pathways, the effectiveness of a WASH intervention in reducing the health burden of GI illness is likely to be modulated by several factors, including the existing drinking water, sanitation, and hygiene conditions. For instance, it is unlikely that a water treatment intervention will have a considerable effect in reducing GI illness if the sanitation and hygiene conditions are poor because people would still be exposed to pathogens when using unimproved sanitation facilities, or when in contact with hands, water, food, soil, and fomites that have been contaminated by unsafe handling of excreta

(Eisenberg et al. 2007). For this reason, it is not very productive to think of one type of WASH intervention as being universally more effective than the others. Rather, the attention should concentrate on using location-specific information to prioritize interventions and on following an approach that seeks to improve all WASH conditions in a balanced way. Furthermore, when tools and resources are available to identify the pathogens that are responsible for the largest share of the health burden, such information should be used to select the intervention or sets of interventions that target the specific pathways of such pathogens.

4. WASH AND DEVELOPMENT

When properly designed, implemented, operated, and maintained, Piped Treated Water and Sewage (PTWS) systems are among the most successful tools that public health practitioners have for reducing risks associated with GI illness and, at the same time, improving the broader living conditions and productive capacities of end users (Mackenbach 2007). However, the extension and proper functionality of PTWS systems outside relatively affluent population centers has been quite limited, leaving billions of people without a realistic expectation of receiving such services in the near future (Mintz et al. 2001). The reasons behind the underperformance and lack of availability of PTWS systems in many developing country settings are complex and diverse, but often include insufficient financial resources, failure to prioritize water and sanitation services, deficient local technical and managerial capacity, an intrinsically sharp gradient of economies of scale that severely disadvantages rural areas, informal and uncertain land tenure, water scarcity, inappropriate design, and political instability (Bakalian and Wakeman 2009; Davis et al. 2008; Pattanayak et al. 2010).

In response to some of the limitations of PTWS, the past decade has seen a growing emphasis on the research, development, and implementation small-scale sanitation control systems and household water treatment and safe storage (HWTS) systems (Mintz et al. 1995). In order to better match the diverse needs of underserved communities, the small-scale and HWTS approach seeks to offer a broader set of technological options, lower the economic barriers, involve more types of stakeholders, and decentralize operation and management responsibilities (Lantagne et al. 2006; Nelson and Murray 2008; Sobsey 2002). As small-scale and HWTS systems have been introduced in more places and expanded in certain regions, several epidemiological studies have shown their potential to reduce GI illness (Arnold and Colford Jr 2007; Clasen et al. 2006; Fewtrell et al. 2005; Kremer et al. 2011). Being a relatively new endeavor, the small-scale and HWTS approach will likely face challenges in the years to come as it seeks to establish itself as a viable and effective alternative to the PTWS. One of the current issues of certain small-scale and HWTS technologies is their low adoption and sustained use outside pilot projects and epidemiological trials (Luby et al. 2008; Mäusezahl et al. 2009). Another challenge for this approach will likely be the limited extension of its impact beyond health improvements, such as meeting the productive needs of households and by contributing to reduce the overburden of time and physical effort invested in WASH management related activities, which mainly fall in the hands of women (Ray 2007).

To address these challenges the small-scale and HWTS approach could greatly benefit from incorporating research methods from currently underrepresented disciplines (e.g. psychology, ethnography, consumer behavior, and human-centered design); internalizing experiences from fields that are different in content but that face similar issues (e.g. improved cook stoves, decentralized energy technologies, and basic goods retailing); and disaggregating units of observation and analysis, such as the household and the community, to better understand the specific needs, preferences, and constraints of the different types of individuals that compose them, and with that information design more effective intervention strategies (Murray and Ray 2010; Ray 2007).

5. EVALUATION OF WASH INTERVENTIONS

WASH interventions are quite heterogeneous and involve different degrees of environmental, education, behavioral, and technological components. For instance, some seek to modify the watershed to protect it from contamination; others are based on the dissemination of information to motivate the formation of hygienic habits; while others involve control or treatment technologies at the household level. Interventions can also range in the degree of direct and economic participation of the target population.

Although several epidemiological studies have measured the impact of WASH interventions, most of them have been of short duration and thus there is very limited evidence of their long-term effectiveness (Fewtrell et al. 2005). A few follow-up studies have documented how the protective effects of certain interventions can vanish after the conclusion of the epidemiological trials. A possible explanation for this observation is that the intensity of the evaluation process itself might have temporarily affected the outcomes by increasing the compliance rate (Arnold et al. 2009). Additionally, a disease transmission model using a Quantitative Microbiological Risk Assessment identifies that even short periods of unreliability in the active component, such as water quality, can erase most of the potential benefits of the intervention (Hunter et al. 2009). Another disease transmission model describes how the effect of water quality interventions in reducing diarrhea is modulated by additional transmission pathways (Eisenberg et al. 2007), suggesting that water interventions are more effective when community sanitation risks are reduced. This scientifically-sound model contrasts with results from a review of epidemiological studies which failed to observe additional benefits of combining two or more WASH interventions (Fewtrell et al. 2005). Other types of synergies that have not been studied enough include those that target households, schools, and workplaces together and those that combine WASH and medical treatment interventions.

With so many complex variables at play, it would be inadequate to extrapolate the results of meta-analyses of epidemiological studies to individual interventions without having more information on how the impact might be modulated by changes in their components and the specific local conditions. Counting with information about these finer details of WASH interventions will be of particular relevance as new alternatives are developed and as current ones are scaled-up in diverse settings.

Evaluations that combine formative and summative objectives and methods are of special value to the WASH field. The formative "Why and how does it work?" questions are better addressed through a holistic, emic, and contextualized perspective using qualitative research methods, such as narrative analysis, oral history, focus groups, in-depth interviews, and participant observation. These methods allow researchers to bring to the forefront and disentangle the most relevant dimensions and variables –internal and external to the intervention– that affect human behavior. Addressing the summative "Does it work?" question requires research designs that maximize internal validity and quantitative methods that discern subtle outcome differences (Hoyle et al. 2002). Experimental designs are the most powerful tools for analyzing causal associations, especially when dealing with highly complex social and biological systems.

By combining formative generation of knowledge with summative rigorous impact measurement, comprehensive evaluations allow stakeholders to make better decisions on what interventions are most appropriate to implement and on how to adapt and develop more effective ones. The selection of the formative and summative mix of an evaluation is likely to depend on many factors and should be done on a case-by-case basis, but in general formative objectives are more important during initial phases of the intervention development process and summative objectives become more critical as the intervention matures and its implementation is expanded.

6. DESCRIPTION OF RESEARCH AREA

My field research is based in rural communities located in Baja California Sur (BCS), Mexico. The communities are small in size, often comprised of a group of 10 to 30 households dispersed across a 2 to 10 km radius. The main economic activities in these communities are goat and cattle ranching, blacksmithing, leatherworking, fishing, and more recently ecotourism and organic farming. Some rural residents also depend on day-labor opportunities in agricultural camps or construction projects in urban areas. Most households are not connected to the electric grid and rely on solar panels to power lightning and communications appliances. Some communities have grocery stores, but most need to seek these and other basic services in cities and larger towns.

The climate in BCS is arid, with most of the rainfall occurring in the late-summer hurricane season. The landscape is carved with hundreds of dry riverbeds that only carry water for a few days following a heavy rain event. Only urban areas and larger towns have piped water distribution systems, which also depend on groundwater. In rural communities, people rely on unimproved springs and shallow wells to meet their drinking, domestic, and productive water needs. Most of these water sources are prone to fecal contamination from nearby latrines and livestock excrement, which can reach the water source premises by direct deposition from the animals, by the settling of dust, or through runoff during rain events. The contamination levels increase even further as water is transported to and stored in the household in *tinajas* (traditional containers made of rock or clay), buckets, or barrels (see Figure 1.1). As documented by the cross-sectional Agua SALud and the longitudinal AquatUVo water quality field studies in BCS, more than 50% of the sources and 90% of the storage containers used by participating households contained *E. coli* (a widely used indicator of fecal contamination) at any given time (Reygadas et al. 2007; Tovar et al. 2005).

Child mortality associated with GI illness has decreased considerably in Baja California Sur over the past two decades (Secretaría de Salud, México 2013). Some factors that possibly contributed to this reduction are the widespread introduction of *Vida Suero Oral* (oral rehydration therapy), the constant hygiene campaigns led by rural health promoters, and the increased access to health facilities due to transportation infrastructure improvements and the construction of new clinics in some towns and communities. In spite of the progress made, gastrointestinal diseases remain the second most common health problem affecting the day-to-day life of rural residents and, according to the Mexican Department of Health, drinking unsafe water is likely to be the main factor associated with them (Secretaría de Salud, México 2013). Such burden of disease negatively impacts: children's performance at school through a combination of absenteeism and impaired ability to learn caused respectively by acute and chronic diarrhea; adults' ability to work due to the impossibility to carryout physical activities during cases of acute diarrhea and the need to take care of sick children; and the household's economy by requiring travel and emergency medical assistance expenditures that can range as high as \$80[2] per event for a family living in a rural community (Baqui et al. 1993).

Figure 1.1: Sources and storage containers commonly used in rural BCS, Mexico[3]

In the mid 1990's, in an effort to reduce GI illness morbidity and in recognition of the government's inability to provide treated piped water to small communities, the Mexican Department of Health launched an intense campaign to promote disinfection of drinking water at the household level. However, the campaign has focused on promoting boiling and chlorination with bleach, which have not been adopted by the population primarily due to the large quantities of wood required to boil all drinking water and the bad taste that results from the use of bleach to disinfect it. With limited alternatives, a growing number of households have started to purchase commercially-bottled water for \$0.60 to \$1.60 per *garrafon* (the 20 L containers that bottled water is typically sold in), a price that low-income Mexicans find difficult to pay on a consistence basis. Additionally, since water is water is sourced, treated, bottled, and transported by purification companies located in distant cities, households' access to safe water ends up depending on a distribution chain that is not always reliable and that is easily disrupted when road access to small communities is cut off during heavy rains. Another limitation of this method is that nearly all the money spent by households on bottled water is effectively piped out from the rural to the urban economy.

In a parallel effort to reduce GI illness morbidity, the Department of Social Development has distributed urine-separating latrines to more than half of the rural households with mixed success. Anecdotally, I have noted that some are used in ways that greatly improve the management and isolation of excreta, while others become highly unhygienic places that can increase the transmission of pathogens through insect vectors and the unavoidable contact of

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[2] All monetary values refer to 2010 U.S. dollars unless otherwise stated.

[3] Photographs taken by Elizabeth Moreno in collaboration with Fundacion Cantaro Azul.

contaminated fomites. One important limitation and missed opportunity of the latrine program is that its infrastructure does not incorporate a dedicated hand washing sink.

Considering the low population density in rural communities, the limited contamination from some unimproved latrines, the easy access of animals to water sources, the use of inadequate drinking water storage containers, and the lack of dedicated hand washing stations, I would conclude that the most effective mechanisms to disrupt the transmission of GI illness are likely to be the disinfection of drinking water, its storage in safe containers, and the promotion of better household and hand-hygiene practices.

Finally, it is important to note that even though the population we are targeting in BCS does not necessarily represent the conditions encountered by communities in the lowest income bracket or with the worst sanitation problems in the world; the region is certainly representative of millions of low to mid-income households located in small rural communities that are unlikely to be served by water distribution and sewage systems in the foreseeable future.

Chapter 2. Development of the Mesita Azul Ultraviolet Water Disinfection System and Program

1. MESITA AZUL PRODUCT DESIGN

The UV Tube is a point-of-use water disinfection system that uses ultraviolet light to inactivate viruses, bacteria, and protozoa at a rapid flow rate without producing unpleasant or harmful disinfection by-products. The UV Tube concept was originally conceived by an interdisciplinary team of UC Berkeley students and professors that recognized that a wide array of safe water options are urgently needed to address the severe and widespread health problems caused by drinking water contaminated with pathogens. Thus, the UV Tube disinfection chamber was designed to be easily-adaptable to meet the needs of a broad range of settings, including: households, schools, health clinics, community kiosks, and self-serving stations located in stores.

A series of tests on an early version of the UV Tube disinfection chamber demonstrated the laboratory efficacy of the system when operated at a flow rate of 5 liters per minute. Based on biological assays with MS2 coliphage virus, the disinfection chamber delivered an average UV dose of 900 ± 80 J/m^2 (95% CI), which is slightly twice the minimum dose recommended by the NSF/ANSI Standard 55 for "Ultraviolet Microbiological Water Treatment Systems". The system was tested using water with an absorption coefficient of 0.01 cm^{-1} and it was estimated to be effective on waters with a coefficient as high as 0.1 cm^{-1} (Brownell et al. 2008). In 2005, I used the specifications of this disinfection chamber to design a version of the UV Tube called the AquatUVo and participated in an interdisciplinary team of five students that tested it in the field in 24 households located in rural BCS. The field study showed that the AquatUVo improved the quality of drinking water and met the needs and expectations of the final users.

In 2006, partly with the objective of taking the UV Tube to the next stage of development, I co-founded Fundacion Cantaro Azul, a non-profit organization based in Mexico that designs, implements, and evaluates water and hygiene programs in underserved communities. During that year I collaborated with members of the UV Tube project at UC Berkeley and Cantaro Azul staff to use a human-centered approach to design a new household version of the UV Tube called the Mesita Azul (small blue table in Spanish)[4]. The Mesita Azul provides a dedicated and permanent space in the household to disinfect water, which seeks to facilitate the creation of a disinfection habit and the maintenance of the routine by reducing the likelihood of its physical displacement. Its design standardizes and simplifies the structure of operation tasks, such as not depending on the use of additional furniture (the AquatUVo was meant to be mounted over an existing table and required the use of an improvised object to support the storage container while it was being filled up with disinfected water). The table-based design and its components are also used to exploit physical constraints that facilitate its use and reduce the frequency of inadequate patterns, like tilting the UV chamber to empty it faster. The Mesita Azul also has clearer indications on

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[4] The Mesita Azul consumes 20 watts of electricity, which can be powered with different types of AC or DC voltage sources, such as solar panels, on-site generators, and the grid.

each of its components and incorporates a graphic manual of the disinfection process, which both seek to improve the operator's mental mappings of the system (Norman 2002).

To obtain early feedback on the operation process and design components, we solicited the help of two rural Mexican families that live close to Santa Rosa, California, in testing the first prototype of the Mesita Azul (see Figure 2.1). Then, I worked with Cantaro Azul to run a small pilot project that tested the second prototype of the Mesita Azul and an implementation program in 14 households located in rural BCS. The AquatUVo and the first two wood-based prototypes of the Mesita Azul were built by us using materials commonly available at hardware stores. After participating in these intensive construction processes, it became clear that we needed to take advantage of manufacturing processes, such as plastic injection molding, to increase the production capacity. As a first step in this direction, I designed the molds for manufacturing the end caps of the disinfection chamber according to the dimensions of the version validated in the lab. We also improved the production capacity by outsourcing the construction of the Mesita Azul to a professional carpenter. In 2007, following these production improvements, I worked with Cantaro Azul staff to roll out a second pilot project in BCS to test the Mesita Azul in a more diverse setting and to refine the program processes. The Mesitas Azules installed as part of this project had a construction cost of $70 per unit. The salary of Cantaro Azul's staff and the fieldwork expenses increased the program costs to a total of $120 per participating household. Out of the 150 targeted households, 143 (95%) adopted the Mesita Azul and committed to pay a $36 contribution fee. Approximately 60% of the households paid the fees on time, 20% paid them late, and the remaining 20% only made partial payments. A follow up visit carried out one year after the Mesitas Azules had been installed showed that 80% of the families were still using the system in a continuous basis to meet their drinking water needs.

Two prototypes installed in Santa Rosa, California

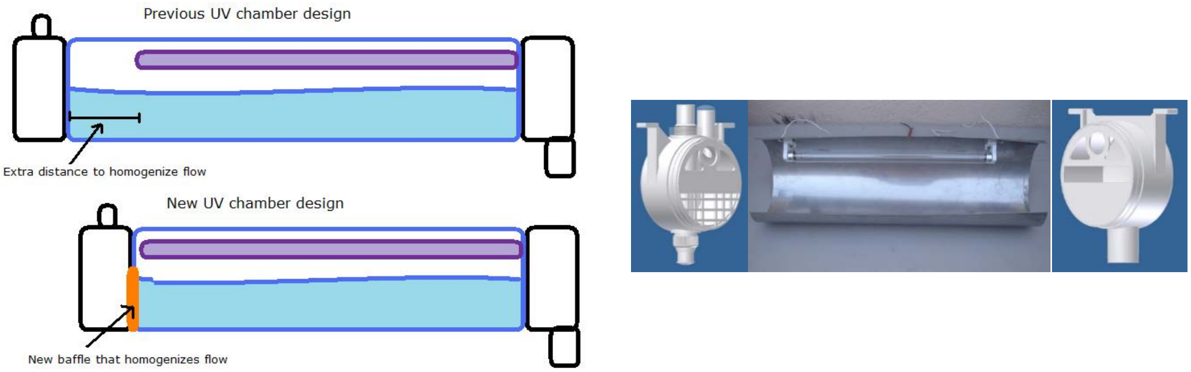
Pilot project with 14 Mesitas Azules installed in BCS

Pilot project with 150 Mesitas Azules installed in BCS

Figure 2.1: Mesita Azul prototypes and pilot projects.

With the positive acceptance of the Mesita Azul in the second pilot study, Cantaro Azul and the UV Tube team at UC Berkeley decided to seek support to expand the implementation of the program. In 2008, Josh Gruber (PhD student at the School of Public Health) and I collaborated with our advisors to develop a research proposal that received a grant from the Sustainable Products and Solutions Program and the Blum Center for Developing Economies. With funding from this grant I was able to make improvements to the disinfection chamber and to design the scalable version of the Mesita Azul. The grant also provided funding for Josh and me to design and carryout a field trial of the Mesita Azul. Josh is using the trial to evaluate the health impact of the Mesita Azul program as part of his dissertation research. Also as part of my dissertation research, I am using the trial to evaluate the field efficacy of the Mesita Azul and to evaluate the factors that affect its adoption and use.

My objectives for modifying the previous version of the UV chamber were to reduce its size and streamline its construction process, while maintaining or increasing the germicidal dose delivered. A smaller chamber would reduce the cost of materials, facilitate transportation from the manufacturing site to the target communities, and result in a more compact Mesita Azul that should fit better in space-constrained households. I started the design process by setting up an experiment where I could observe and measure the dispersion of pulses of a highly saline dye as they flowed through the disinfection chamber. The previous version of the UV chamber had a 10 cm buffer zone on the inlet side to allow for the water flow to become more homogeneous before passing underneath the lamp (see Figure 2.2). After observing the flow pattern at different flow rate regimes, I developed the hypothesis that the water flow could be homogenized with a baffle in the inlet end cap without the need for a buffer zone, and thus the length of the chamber could be reduced to the length of the lamp (not counting the end caps). After testing several prototypes, I designed a baffle that homogenized the vertical velocity profile by slowing down an otherwise highly rapid flow in the water surface and homogenized the horizontal velocity profile by using a rectangular lattice made with a mesh structure that amounts to 36% of the cross-sectional area[5]. This new baffle led to a narrower pulse dispersion. Then, I proceeded to test the new chamber design using biological assays with MS2 coliphage virus[6], obtaining an estimated dose of 1,224 ± 66 J/m² (95% CI), which is higher than the dose delivered by the previous version. With these results I proceeded to design a plastic injection mold for the baffle, which also eliminated the need of cumbersome lamp holders by incorporating a mounting area for the lamp.



Differences between previous and new disinfection chambers.

Design of inlet latticed baffle and outlet wier.

Figure 2.2: Longitudinal views of UV chambers and their components.

My initial objectives for designing a new version of the Mesita Azul were to: reduce costs and increment the production capacity by switching from a wood-based to a plastic injected

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[5] Mesh characteristic was suggested by Prof. Evan Variano in a personal conversation.

[6] I could not have done these tests without the invaluable support of Prof. Kara Nelson's lab members: Mike Fisher, Dave Love, and Gordon Williams.

structure; increase transportation efficiency and decrease material costs by reducing its size; make the disinfection process easier; and reduce barriers to access drinking water. I started the design process by documenting the interactions of users with AquatUVos and previous versions of Mesitas Azules in BCS (see Figure 2.3).

The main insights that I obtained through this observation phase were that: people avoided placing the garrafon directly on the ground and often relied on improvised materials to create a base for the garrafon and Mesita Azul; it is unlikely that users will fill an additional garrafon when the garrafon underneath the Mesita Azul still has water, which limits the availability of disinfected water to one access point in the household; when the pump broke, several users perceived that the whole disinfection system had stopped working and discontinued its use until the pump was fixed or replaced. Considering this information, the plastic injection molding constraints, and our objectives I created several sketches of user interfaces. I reviewed the sketches with my colleagues at Cantaro Azul and, with their feedback, I focused on developing two aesthetically different design concepts: a stylish and fresh-looking curved table based on the contour of an ocean wave and an austere but elegant table with rounded corners.

We built two small size but detailed mockups that I used to solicit feedback from a larger population, including potential users. Preferences for the two designs were almost split evenly and were rarely strong in a particular direction. Informed by conversations and my own analysis, I selected the rectangle with round corners design because I considered that: its robust looking structure would inspire more trust, which could unconsciously affect the perception of its capacity to disinfect water; its neutral style would produce a lower rate of negative reactions when expanded to a broader segment of the population; and, although it was more austere, it would still perceived as highly aesthetically appealing.


Improvised support for holding container while using AquatUVo.

Improvised base to separate *garrafon* from the ground.

The height is set to fit the *garrafon* and separate it from the ground.

Figure 2.3: Evolution of UV Tube designs and analysis of how users adapt it to meet their needs.

After selecting the design concept, I built several wooded full-scale mockups to test its dimensions, structural integrity, and the performance of the operation processes. Through a highly iterative process between the mockups and the computer screen, I used the Autodesk

Inventor 3D software to design the plastic injection molds for the scalable version of the Mesita Azul. Through such efforts, the Mesita Azul interface is now partly manufactured at a plastic injection molding facility with a production capacity of 400 per day and its production cost was reduced by half to $10, contributing to a 15% reduction of the full cost of the household system, which for this program was approximately $57 per unit.

2. MESITA AZUL SAFE WATER PROGRAM

Based on our experience of the first two pilot projects, Cantaro Azul staff and I developed a program to expand the implementation of the Mesita Azul. The overall goal of the Mesita Azul Program is to generate a sustained practice of drinking safe water among the target population with ultimate aim of reducing GI illness. The program seeks to achieve its goal through a series of processes that are grouped in five sequential phases: regional assessment, community assessment, presentation of program to community members, installation of Mesitas Azules, and a series of follow-up visits (see the Impact Model of the program in Figure 2.4).

The main objective of the **Regional Assessment** is to adapt the program to the characteristics of the region. Information about the region is collected both through existing databases and direct visits to approximately 10-20% of the target communities. This phase is also used to develop partnerships with key stakeholders.

The first field visit consists of carrying out a **Community Assessment** in which Cantaro Azul staff evaluates the sanitary risk of water sources, documents the local water transportation and storage practices, assesses the technical and social feasibility of the project, and records demographic data. All this information is analyzed for logistical purposes, but most importantly to generate results that can be presented to community members with the objective of creating awareness of water contamination problems (if they exist) and motivation to participate in the program. Another objective of the community assessment is to generate rapport and credibility with community members and stakeholders.

Once the needs assessments have been carried out and the Mesitas Azules constructed, Cantaro Azul staff announces and schedules the **Community Presentation**. The meeting is led by Cantaro Azul staff through motivational messages and participatory techniques. The meeting has the following sequence: 1) present relation between drinking water and health; 2) share results of the community assessment; 3) present common safe water options; 4) present Mesita Azul as an alternative option and demonstrate how it works; 5) explain benefits and requirements for enrolling in the program[7]; 6) provide a platform for enrollment in the program; 7) identify local community members that will be recruited and trained to repair Mesitas Azules; and 8) schedule installation visits.

The third visit to the community consists in collecting payments, **Installing Mesitas Azules**, training households how to operate and maintain their new systems, and training repair teams.

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[7] The requirements for participating in program are: to commit to only drink water treated with Mesita Azul; to contribute with onetime payment of MXN$250 (USD$20) or MXN$300 (USD$24) in installments within 6 months; and to assume responsibility for maintaining Mesita Azul.

One month after the installation, Cantaro Azul staff visits each of the participating households to provide a **Short Term Follow-Up** of the program. During this visit, Cantaro Azul staff seeks to strengthen household motivations towards safe water and collects payments.

Four to six months after the installation, Cantaro Azul staff visits each of the participating households to provide a **Medium Term Follow-Up** of the program. During this visit, Cantaro Azul staff seeks to strengthen household motivations towards safe water, retrains repair teams, addresses any potential technical problems, and collects any overdue payments.

The **Long Term Follow-Up** consists in supporting the repair teams in obtaining the necessary replacement parts and visiting households that are known to have complex technical problems with their systems.

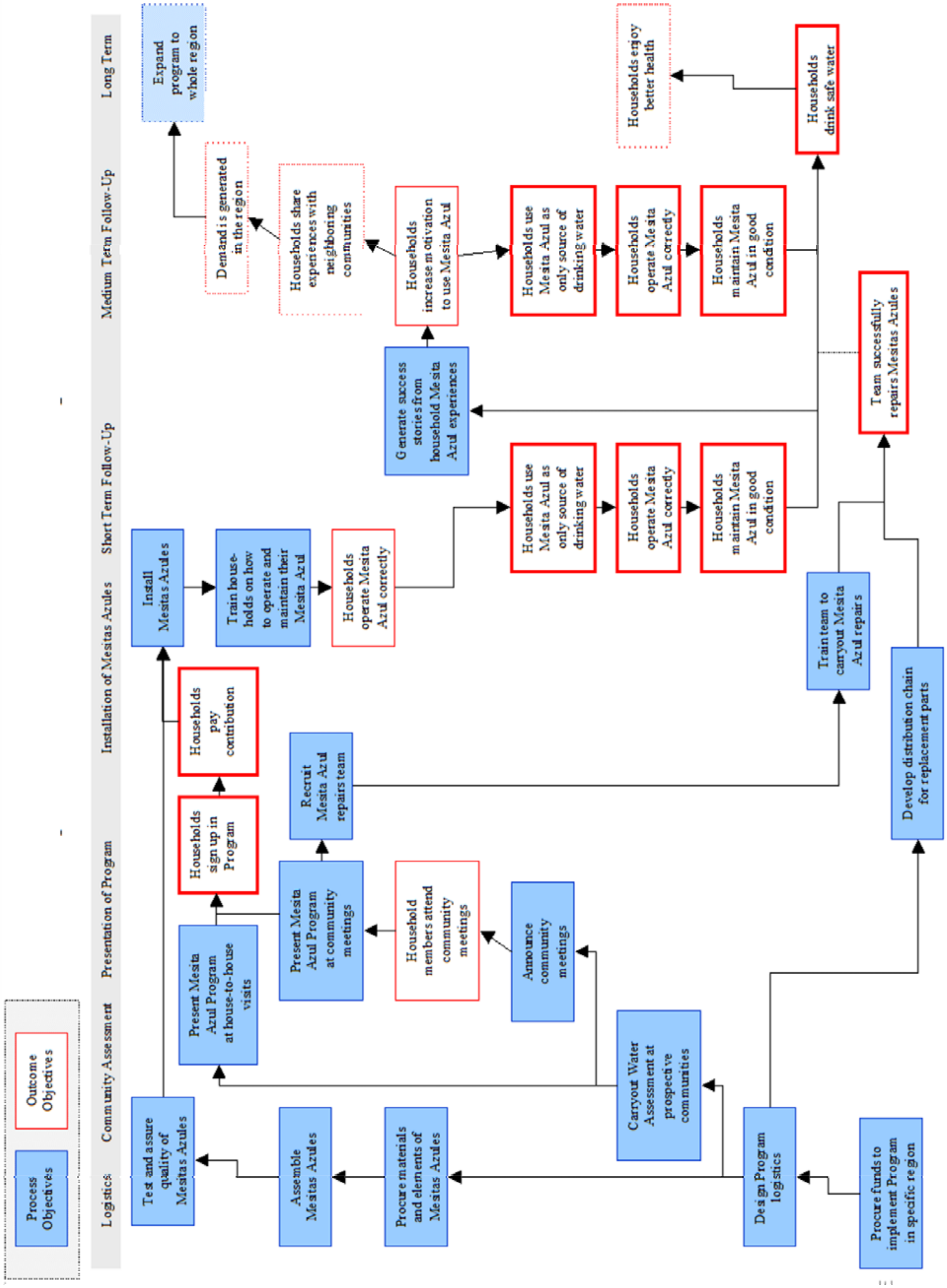

Figure 2.4: Impact Model of the Mesita Azul Program.

Chapter 3. Evaluating User Compliance for Home Water Treatment and Storage Systems: A Study of UV Disinfection in Rural Mexico

1. INTRODUCTION

Many households in developing countries rely on contaminated and untreated drinking water sources (Bain et al. 2014a, 2014b; Shaheed et al. 2014), contributing to gastrointestinal illness and other health risks (Hunter et al. 2010). Even piped water quality is often unreliable because of poorly-maintained treatment or distribution systems (Ercumen et al. 2014; Lee and Schwab 2005). Household water treatment and safe storage (HWTS) systems aim to treat water at the point of use, making it safe to drink. To meet the diverse needs of underserved communities, the HWTS approach offers a broad set of technological options, lower the economic barriers to access, and decentralize operation and management responsibilities (Clasen et al. 2009; Lantagne et al. 2006; Sobsey 2002).

HWTS systems need their users to adhere to (or "comply" with) the requirements of the program, such as operating the system correctly and consistently, purchasing consumables and replacement parts, etc. Studies have shown that HWTS can improve health outcomes (Arnold and Colford Jr 2007; Fewtrell et al. 2005; Sobsey 2002), but low compliance is the norm outside of pilot projects and epidemiological trials (Albert et al. 2010; Arnold et al. 2009; Luby et al. 2008; Mäusezahl et al. 2009; Parker Fiebelkorn et al. 2012). Quantitative Microbiological Risk Assessment models predict that the health benefits from water quality interventions drop with even occasional consumption of untreated drinking water (Brown and Clasen 2012; Enger et al. 2013a; Hunter et al. 2009). User compliance is essential for HWTS to achieve its intended health effects, and must be better understood to improve safe water programs (WHO and UNICEF 2012).

Compliance remains unevenly studied and inconsistently defined in the HWTS literature. Many previous HWTS studies have assumed compliance based on water quality, residual disinfectant levels, or 'occasional observation' (Clasen et al. 2009; Parker Fiebelkorn et al. 2012). More rigorous metrics for assessing compliance are critical for interpreting and addressing the household-level drivers of HWTS effectiveness. HWTS interventions usually require behavior changes that are inconvenient for household members, and research has documented the challenges of changing social interactions, norms, preferences, and perceptions (Figueroa and Kincaid 2010; Mosler 2012). Outside of the HWTS sector, it has been shown that small adjustments towards greater user convenience can lead to significant improvements in product uptake (Banerjee et al. 2011; also Bertrand et al. 2006). In this chapter we present a comprehensive approach to HWTS compliance, and test if subtle changes in the user convenience of a HWTS program can improve compliance.

We develop the Safe Drinking Water Compliance Framework, disaggregating compliance into five components – Adoption, Access, Knowledge, Habit, and Exclusive Use. This framework can be applied to any household-based drinking water technology. We apply this framework to an HWTS system that uses ultraviolet (UV) light to disinfect water, and was delivered to rural communities in Mexico between 2009-2011 as part of safe water program. We further extend the framework to the most common pre-existing safe water practice utilized by these communities prior to the introduction of the UV-based HWTS: purchase of commercial bottled water in 20-L, plastic, narrow-necked containers (*garrafon*-bottled water). We assess the levels of compliance within the UV-based HWTS intervention and evaluate the strengths and weaknesses of the outreach program, which aimed to support adoption and use of the UV system, in the context of the proposed Compliance Framework. We evaluate two variants of the program (Basic and Enhanced) to test if modest improvements in the level of convenience could cause significant improvements in compliance. We carry out a full cost analysis of each variant to see if the added conveniences are worth the cost of any additional uptake and use of the system. We find that the UV safe water system significantly increased the study households' habit of consuming safe water, but that even the Enhanced program variant saw compliance deteriorating over an eight-to-ten month period.

This study was conducted as part of a larger research project measuring the program's impact on drinking water quality and health (Gruber et al. 2013), as well as the UV technology's field efficacy and risks associated with post-treatment contamination.

2. BACKGROUND

2.1 STUDY AREA

This study took place in 24 rural communities in Baja California Sur, Mexico. The region is hot and dry, with less than 200 mm annual average precipitation. The communities had 20 to 70 inhabitants whose primary economic activities were livestock ranching, small-scale farming, and fishing. Communities were located one to four hours away from larger towns, mostly via unpaved roads. Only 14% of households had electrical grid connections; 80% used small solar panels for lighting and communication. None of the communities had functioning piped water systems. At the beginning of the study, most people relied on untreated water from local springs and shallow wells for drinking water, though some purchased *garrafon*-bottled water from urban vendors. Those collecting local water stored it in plastic buckets, 200 L barrels, and traditional containers made out of rock or clay (*tinaja*s). Drinking water was mostly extracted by dipping a cup into these containers (Gruber et al 2013).

2.2 MESITA AZUL PROGRAM: BASIC AND ENHANCED

Fundación Cántaro Azul, a non-profit organization based in Mexico, collaborated with our research team to develop an HWTS program consisting of: an ultraviolet (UV) disinfection system (or Mesita Azul, meaning "little blue table" in Spanish), a safe storage container (a 20 L *garrafon*), and a series of outreach activities to support adoption and use of the system. The Mesita Azul contains a UV lamp (15 W; 254 nm) to inactivate bacteria, viruses, and protozoa. The germicidal dose deliver by the system exceeds common HWTS and UV disinfection standards (NSF 2002; WHO 2011a) to ensure proper disinfection throughout the lifetime of the system (Gruber et al 2013). The Mesita Azul does not change the taste, temperature, or color of water. We refined the Mesita Azul program for these rural households through an iterative process of design, field tests, and user feedback, prior to rolling it out to a larger set of communities.

Cántaro Azul designed the Mesita Azul as an aesthetically appealing and user-friendly system for treating water (see Figure 3.1). To operate the system, users had to follow the follow six simple steps: (1) turn on the switch and look through a plastic window to check that the UV lamp worked; (2) pour water through a straining cloth into the bucket; (3) open the bucket's valve; (4) wait for water to flow by gravity through the disinfection chamber and into the *garrafon*; (5) close the bucket's valve and open the drain; and (6) turn off the switch. The system disinfects 20 L of water in five minutes. The garrafon included a cloth wrap which, when wetted, could keep stored water cool.

Figure 3.1: Image of the Mesita Azul system includes bucket for source water, UV disinfection chamber, and safe storage container (*garrafon*) for treated water.

The research team developed two variants of the Mesita Azul program: Basic and Enhanced. The Basic program was minimalist and included only those features that were deemed essential to promote the system's adoption, use, and maintenance. The program consisted of four sequential activities: community assessment, community presentation, installation of UV systems, and follow-up visits. During the community assessment, program staff established relationships with key stakeholders, assessed the feasibility of the project (e.g. microbial rather than chemical contamination in water sources, presence of electricity, etc.), and recorded demographic data. During the community presentation, they discussed water and health, water quality in the region, pre-existing, available water treatment options, the Mesita Azul, and the benefits and requirements of the program. They then launched the enrollment process and recruited community volunteers to maintain and repair the systems. Households could enroll in the program if they committed to drinking only disinfected water, made a $20 (MXN$250) one-time payment or a $24 (MXN$300) payment over six months, and assumed responsibility for maintaining the UV system. In the third visit to the community, program staff installed the UV system with its safe-storage container in each enrolled household, and trained one member of the household on how to operate the system. Four to six months after the installation, they carried out a follow up visit to retrain households, address any technical problems, and collect any outstanding payments.

The Enhanced variant of the Mesita Azul program included additional conveniences and guarantees meant to reduce "small hassles" (Bertrand et al. 2006) to adoption and compliance. In addition to the features of the Basic variant, the Enhanced variant reported water quality to each household, offered a six-month money-back satisfaction guarantee, trained two (not one) household members on how to operate the system, provided two *garrafones* (not one) per system, and added a follow-up visit within one month of the installation (see Table 3.1).

Table 3.1: Compliance barriers and the strategies used by Basic and Enhanced programs to minimize them.

Barriers	**Basic Program**	**Enhanced Program**
Poor information	Regional water quality results	Individual water quality results for each household
Limited economic resources	Six month system guarantee	Six month system and money-back guarantee
Low operator capacity	Train one person per household	Train two people per household
Low user convenience	One safe storage container	Two safe storage containers
No safe water habit	Follow up every six months	Follow up within one month and then every six months

2.3 SAFE DRINKING WATER COMPLIANCE FRAMEWORK

Our primary outcome measure for this study, specified *a priori*, was the habit of consuming safe water. For a household to meet our primary our primary outcome measure, the interviewee had to report that their the last glass of water consumed as well as their most common source of drinking water was from either UV-treated water stored in a garrafon or from a purchased *garrafon*.

To assess the potential impact of the Mesita Azul program(s), we needed to measure household compliance. Compliance is a multi-part phenomenon that is inconsistently operationalized in the HWTS literature; definitions of compliance range from simple adoption (with no measures of actual use) to correct and consistent use (Clasen et al. 2009). We developed a comprehensive framework to define and measure all the components necessary to achieve the intended health benefits of safe water programs. Unpacking "compliance" into its specific tasks for a specific program thus shows which components of compliance are most challenging for which household-types, and where strengthening the program will be most effective.

Our Safe Drinking Water Compliance Framework consists of five components: Adoption, Knowledge, Access, Habit, and Exclusive Use, all of which are directly related to procuring and consuming safe water. Adoption is the initial acceptance of a safe water practice or technology; Knowledge is the information necessary to carry out the safe water practice; Access is the possibility of carrying out the practice within the means and resources available in everyday life; Habit is an established and dominant practice; and Exclusive Use is the practice of drinking only safe water within the household. We disaggregated each component into procurement and consumption. Procuring and consuming safe water are interlinked in a household, but are distinct processes, carried out at different times and places, and by different household members with their own motivations and barriers. The operational definitions of procurement and consumption can be adapted to the characteristics of specific safe water programs.

For our study, we adapted the compliance framework to purchased *garrafon*-bottled water (see Table 3.2) and to the Mesita Azul program(s) (see Table 3.3). Tables 3.2 and 3.3 document the operational definitions for each component and the measures we used during household visits to verify compliance or non-compliance. We framed our interview questions (through pre-survey piloting) such that self-reported information on habitual and exclusive consumption of safe water had low likelihoods of recall bias and social desirability bias. We did not measure consumption under Adoption because we expected it to be similar to procurement, but it could be relevant where disaggregated measurements across e.g. gender or age are needed. Our operational definitions and measures are not an exhaustive list. They are tailored to the specific safe water practices, observable measures, user reports, and the time frame of our study.

3. METHODS

3.1 STUDY DESIGN

We conducted a cluster-randomized control stepped wedge trial to evaluate the impact of Mesita Azul program, and to compare the effectiveness of the Enhanced and Basic program variants on compliance with safe water practices. We recruited 444 households in the 24 study communities. The study lasted 18 months and consisted of a baseline survey followed by six consecutive intervention and evaluation steps (see Figure 3.2). The communities received the intervention in a randomized sequence, with four new communities being enrolled in each step. Among the four communities that crossed over from control to intervention in each step, a second randomization process was used to assign two communities to the Enhanced program variant, and the other two received the Basic program variant. By the end of the trial, all the communities were enrolled in one of the two program variants.

The stepped wedge design (randomly sequenced rollout of the program) created intervention and control periods that allowed us to compare the water quality impacts with and without the safe water program (reported in Gruber et al 2013); the secondary randomization process was designed to identify any differences in the effectiveness of the Enhanced and Basic programs with respect to increasing access and use of safe water habits.

Table 3.2: Safe Drinking Water Compliance Framework adapted to *garrafon*-bottled water.

Components	**Operational Definitions**	**Measurement**
Adoption		
Procurement	Household possessed garrafon-bottled water.	Interviewer verified presence of *garrafon*.
Consumption	Not documented.	Not applicable.
Knowledge		
Procurement	Interviewee knew how and where to get *garrafon*-bottled water.	Interviewee reported location where *garrafon*-bottled water could be obtained.
Consumption	Interviewee recognized garrafon-bottled water as being of better quality than untreated water.	Interviewee compared *garrafon*-bottled water quality with other sources.
Access		
Procurement	*Garrafon*-bottled water could be purchased within 1 km from household (human right to water).	Interviewer documented *garrafon*-bottled water availability at the community level.
Consumption	*Garrafon*-bottled water was present in the home.	Interviewee reported *garrafon*-bottled source and interviewer verified presence of water.
Habit		
Procurement	Household members obtained *garrafon*-bottled water at least once every five days.	Interviewee reported frequency of purchase.
Consumption	Interviewee reported that her/his last glass of water came from, and her/his most common drinking source was, *garrafon*-bottled water.	Interviewer recorded from where interviewee had drunk his / her last glass of water. Interviewee also reported most common source of drinking water.
Exclusive Use		
Procurement	Not documented.	Not applicable.
Consumption	Interviewee reported consuming only *garrafon*-bottled water while in her/his household during the past seven days.	Interviewer walked interviewee through all water access points in the household and asked if she/he had consumed water from it in the past seven days.

Table 3.3: Safe Drinking Water Compliance Framework adapted to the Mesita Azul program.

Components	Operational Definitions	Measurement Details
Adoption		
Procurement	Household acquired a UV system.	Interviewer verified presence of system during visit.
Consumption	Not documented.	Not applicable.
Knowledge		
Procurement	Operator knew and carried out UV system operation steps adequately.	Interviewer evaluated operator and asked to treat water.
Consumption	Interviewee recognized UV treated water as better quality than untreated water.	Interviewee compared UV treated water quality with other sources.
Access		
Procurement	UV system worked and was readily usable in its location and condition.	Interviewer verified functionality of system and feasibility to operate it.
Consumption	UV treated and safely-stored water was present.	Interviewee reported treatment and interviewer verified presence of water.
Habit		
Procurement	A household member operated UV system at least once every five days.	Interviewee or system operator reported frequency of operation.
Consumption	Interviewee reported that her/his last glass of water came from, and her/his most common drinking source was, UV treated and safely-stored water.	Interviewer recorded from where interviewee had drunk his / her last glass of water. Interviewee also reported most common source of drinking water.
Exclusive Use		
Procurement	Not documented.	Not applicable.
Consumption	Interviewee reported only consuming UV treated and safely-stored water while in her/his household during the past seven days.	Interviewer walked interviewee through all water access points in the household and asked if she/he had consumed water from it in the past seven days.

The four communities that were enrolled in the program during the last step received an additional visit from the evaluation team to measure study outcomes. This allowed us to compare the Basic and Enhanced program variants using compliance data from the first two visits after the intervention. We also measured the evolution of compliance through time in a subset of eight clusters, with data from the first and the fifth observation visits after the intervention (months 0-2 and 8-10, respectively).

Free and informed consent of the participants was obtained and the study protocol was approved by the Office for the Protection of Human Subjects at the University of California, Berkeley (Protocol# CPHS 2009-1-47, approved on 03/18/2009). We registered this study at ClinicalTrials.gov (NCT01637389).

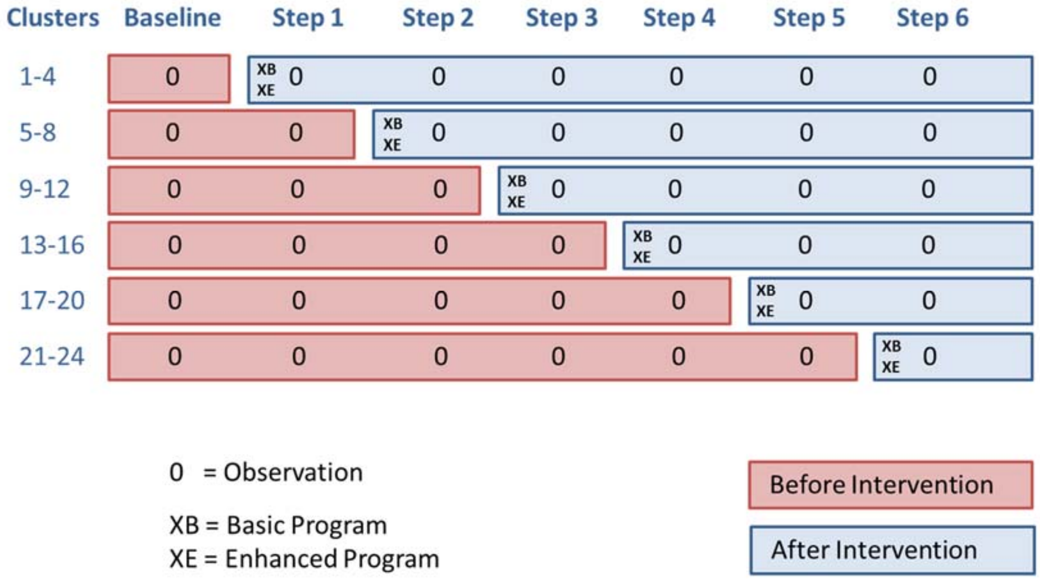

Figure 3.2: Study Design: cluster randomized control stepped wedge trial.

3.2 DATA COLLECTION AND ANALYSIS

We defined safe water post-intervention as water that was treated and stored in a narrow-necked container. Throughout the study we observed households with commercial *garrafon*-bottled water, as well as in-home chlorination, boiling, and UV disinfection. Despite over 10 years of promotion by health workers, we found safely stored chlorinated or boiled water in less than 1% of household visits (10 of 2,601 observations). Given the limited number of observation for these disinfection strategies, we included only garrafon-bottled water and UV disinfected water in our compliance analysis.

We measured compliance rates using the definitions in Table 3.2 for households in Control periods, in Tables 3.2 and 3.3 for households in Intervention periods, and in Table 3.3 for households in Enhanced and Basic program communities. A fully compliant household would meet each procurement and consumption criterion for all five compliance components in either table. However, we defined the primary outcome of the study as the habit of consuming safe water (i.e., treated with Mesita Azul and stored in garrafon or purchased garrafon).

We carried out multiple comparisons in this study. To maximize internal validity of our research design, we specified the primary outcome measures *a priori*. Following Feise (2002), rather than adjusting the statistical analysis of secondary outcome measures, we suggest that the results of our secondary outcome comparisons should be treated with less confidence because of the increased probability of Type I errors. We divided our analysis and results into summative evaluation and formative research components. We used the summative approach to rigorously measure compliance with the habit of consuming safe water, and the formative approach to identify drivers of compliance. We used an intention-to-treat analysis for measurements and comparisons of compliance in the summative evaluations and in most formative research components. We carried out secondary comparisons to provide more information about the structure of compliance and to compare results within similar groups of households.

We managed our databases and carried out our statistical analyses using Stata 12 (Stata Corp, College Station, TX, USA).

3.3 COST-EFFECTIVENESS OF USER COMPLIANCE

We assessed if small program changes intended to improve user convenience could be a cost-effective strategy to increase compliance. We calculated the costs of implementing the Enhanced and Basic interventions per household that met specific compliance outcomes. We aggregated costs of input and process data for each program variant (V), calculated average costs per household targeted by a program (CHT), and *additional* costs per household that adopted the program (CHA). We estimated total program costs (C) within a given period and a given variant as a function of the number of households targeted (N_T) and the number of households that adopted (N_A). By definition, $N_A \leq N_T$.

$$C (V, N_T, N_A) = (CHT_v \text{ x } N_T) + (CHA_v \text{ x } N_A)$$

We calculated the cost-effectiveness (CE) of the program by dividing the program costs (C) by the effects (E_i), where the effects are the observed compliance rate for a particular measure of compliance (*i*).

$$CE (C, E_i) = C (V, N_T, N_A) \ / \ E_i$$

We computed the cost-effectiveness of achieving the habit of consuming safe water (our primary compliance outcome) in the Enhanced and Basic program communities during months 0 – 4 following the intervention. As an exploratory exercise, we also computed the cost-effectiveness of secondary outcomes for this time period, and the evolution in time (months 0-2 vs. months 8-10) of the cost-effectiveness of the safe water habit in both communities.

4. RESULTS

4.1 USER COMPLIANCE IN INTERVENTION AND CONTROL PERIODS

As reported earlier (Gruber et al 2013), random assignment of intervention (I) and control (C) periods produced equivalent groups across a wide range of observable baseline characteristics. Measured baseline covariates, weighted by time contributed to intervention and control periods, included age (<5 years: I=6%; C=6%), gender (female: I=46%; C=45%), education (only elementary: I=20%; C=20%), drinking water quality (<1 *E. coli* organism/100 mL: I=41%; C=39%), access to consuming safe water (*garrafon*-bottled water: I=21%; C=22%), and hygiene conditions (feces in yard: I=33%; C=36%).

For the primary outcome of the Compliance Framework, we observed a risk difference of 30.9% (95% Confidence Interval (CI): 27.4%, 34.4%) in the habit of consuming safe water between intervention (both program variants combined) (49.7%) and control (18.8%) periods. After accounting for clustering and time effects, we obtained an adjusted risk difference of 35.5% (95% CI: 23.4%, 47.6%). The habit of consuming treated and safely-stored water during control periods relied solely on *garrafon*-bottled water (18.8%); during intervention periods it was made up of UV disinfection (39.0%) and *garrafon*-bottled water (10.7%).

We present the secondary outcomes of the Compliance Framework in Figure 3.3. We observed three general trends. First, compliance rates were more than double during intervention periods, compared to control periods across all compliance components; all differences were statistically significant. Second, the intervention resulted in higher compliance rates in procurement than in consumption within the Knowledge, Access, and Habit components. Finally, compliance rates decreased in both groups as the definition of compliance shifted from Adoption to the Exclusive Consumption of safe water.

The observed drop along the compliance components from Adoption to the Habit of safe water (procurement) was proportionally less pronounced in intervention (70.6%) than in control (34.9%) periods, while the drop between Access to and Exclusive Use of safe water (consumption) was more pronounced in intervention (63.4%) than in control (73.3%) periods (see Figure 3.3) Contingent on access to safe water, the habit of consuming such water was the same between intervention (77.4%) and control (80.4%) periods. After intervention, and contingent on access to safe water, more households that had *garrafon*-bottled water at baseline consumed only safe water (70.2%) than those that did not (52.0%).

4.2 USER COMPLIANCE IN ENHANCED AND BASIC PROGRAMS

Random assignment of Enhanced (E) and Basic (B) programs did not produce fully equivalent groups, likely due to the small number of randomized units (24 communities split in two groups). By chance, the Enhanced program communities were further from urban centers, with lower rates of elementary schooling and baseline *garrafon*-bottled water consumption. Measured baseline covariates included age (<5 years: E=6%; B=6%), gender (female: E=46%; B=45%), education (only elementary: E=16%; B=25%), drinking water quality (<1 *E. coli* organisms/100 mL: E=40%; B=41%), Access (consumption) to safe water (*garrafon*-bottled water: E=12%; B=30%), and hygiene conditions (feces in yard: E=34%; B=35%).

For the primary outcome of the compliance framework, we observed a risk difference of 17.4% (95% CI: 10.3%, 24.5%) between the Habit of consuming UV-safe water in the Enhanced (50.5%) and Basic (33.1%) programs. After accounting for clustering effects, the time of observation, and the rate of *garrafon*-bottled water use during baseline, we obtained an adjusted risk of 15.0% (95% CI: 4.7%, 25.3%).

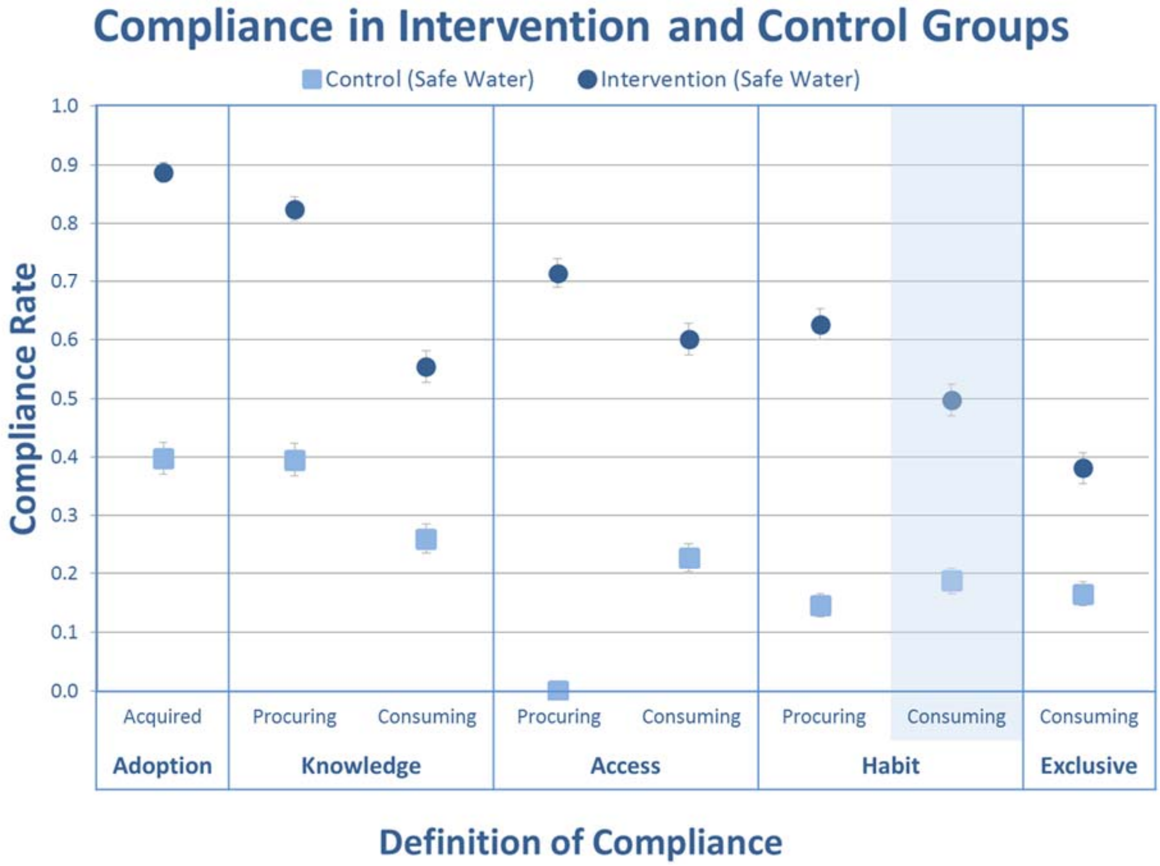

Figure 3.3: Compliance rates for each component of Compliance Framework for consumers of safe water (purchased *garrafon*-bottled water) during control periods (N=1,255) and consumers of safe water (UV treated or purchased *garrafon*-bottled water) during intervention periods (N=1,346).

We used the Safe Drinking Water Compliance Framework to measure the series of secondary outcomes; we present these results in Figure 3.4. Compliance rates for UV Adoption and all procurement measures were approximately 10% higher in Enhanced program communities; Access (consumption) was 18% higher and Exclusive consumption was 8% higher. Differences were statistically significant. There was no difference in the Knowledge (consumption) component.

In an analysis of compliance contingent on adoption of the UV system, we found that the Enhanced program resulted in slightly higher compliance rates for all the procurement measures, and significantly higher rates for Access and Habit (consumption). The Basic program resulted in a higher Knowledge of consumption and there was no difference for the Exclusive consumption component. Differences across Knowledge, Access, and Habit (consumption) were statistically significant.

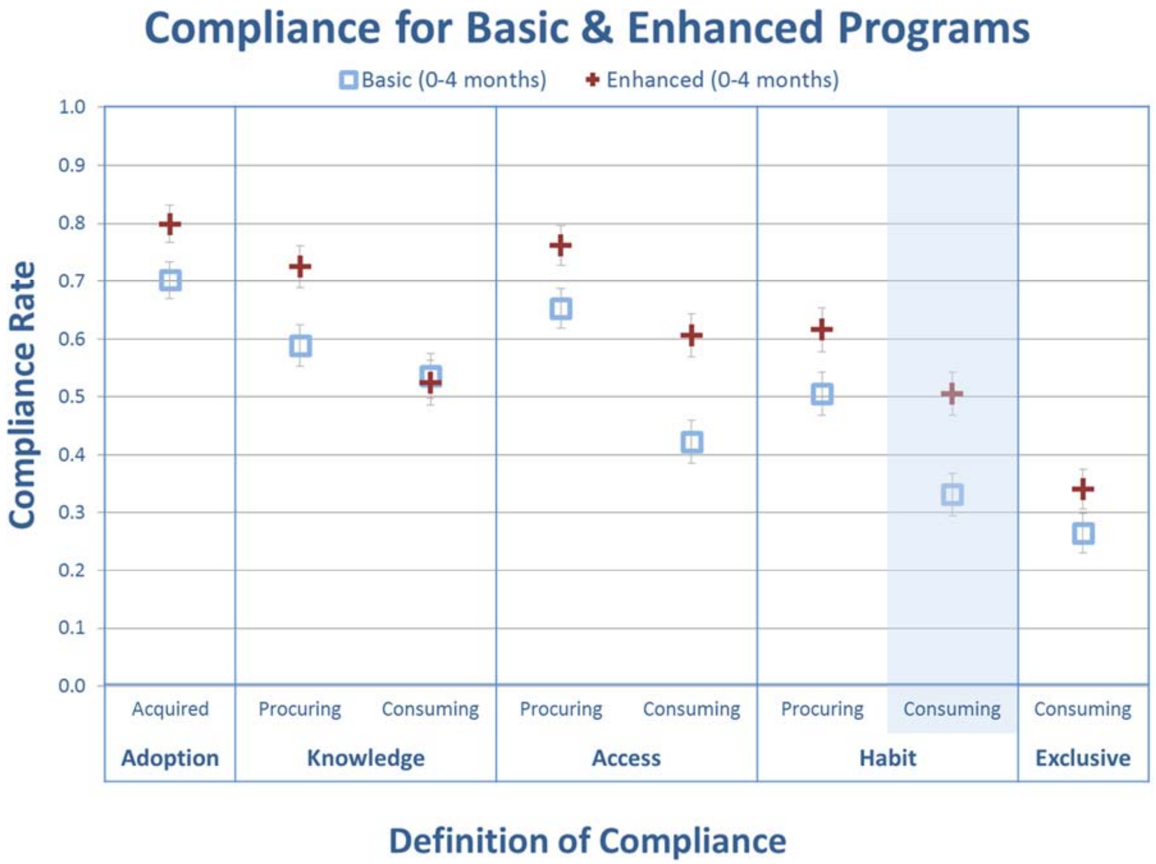

Figure 3.4: Compliance for Basic (N=352) and Enhanced (N=363) programs.

During baseline, the Habit of consuming safe water, achieved solely through *garrafon*-bottled water, was lower in (future) Enhanced communities (11.3%) than in (future) Basic communities (25.0%). During the second visit post-intervention, the safe water consumption Habit, comprising *garrafon*-bottled water and UV disinfection, increased to 55.5% (*garrafon*-bottled=5.0%; UV=50.5%) in Enhanced communities and 50.1% (*garrafon*-bottled=17.0%; UV=33.1%) in Basic communities.

4.3 Evolution of User Compliance through Time

In our analysis of the evolution of compliance through time, we found that the Habit of consuming UV water remained constant in communities that received the Basic variant. It fell sharply in Enhanced communities from 64.7% (first two months following the intervention) to 39.7% (eight to ten months after the intervention). At the end of eight-to-ten months the Habit of drinking UV water was equivalent across Enhanced and Basic program communities.

Compliance rates of most procurement measures increased slightly with time for both program variants; consumption measures remained constant for Basic program communities and mostly decreased for Enhanced program communities. Of these differences, only the reduction in the consumption Habit across time within the Enhanced variant was statistically significant.

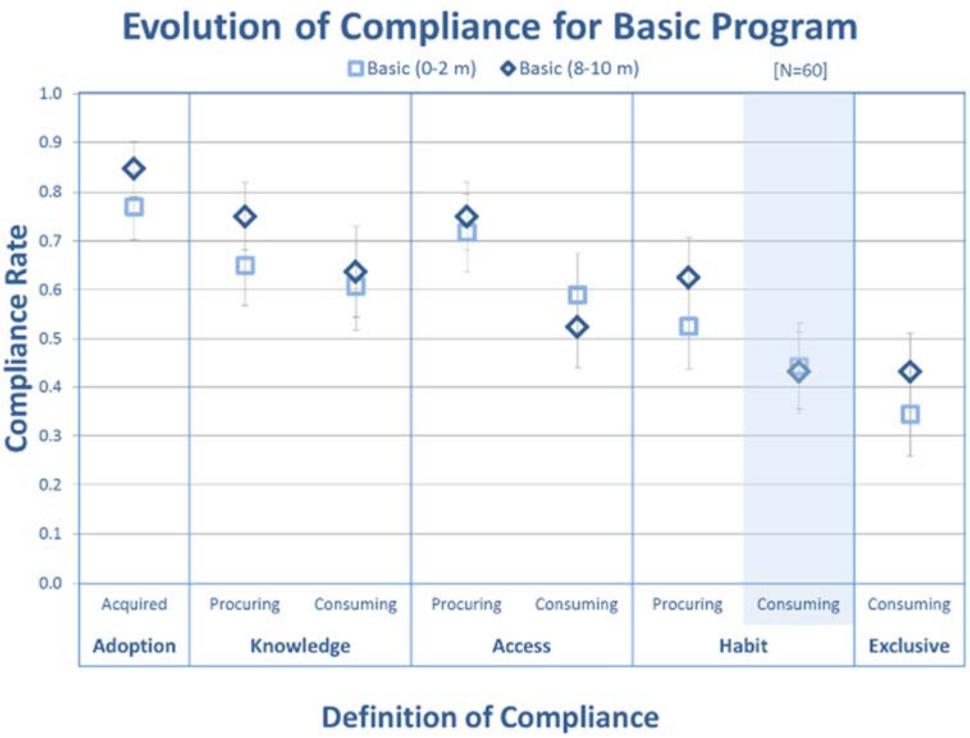

Figure 3.5: Evolution of compliance, Basic program: 0-2 months (N=61) 8-10 months (N=65).

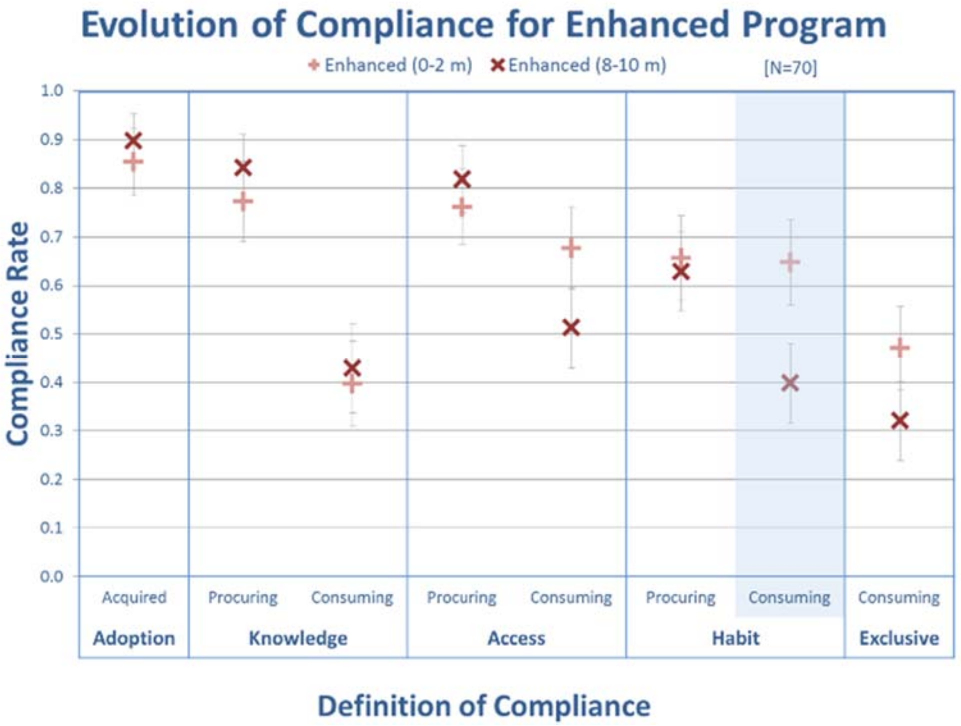

Figure 3.6: Evolution of compliance, Enhanced program: 0-2 m (N=68) 8-10 m (N=78).

4.4 Cost-Effectiveness of User Compliance

Unlike many HWTS cost studies, we calculated the full costs of the Mesita Azul program, from the initial community assessments all the way to the follow-up visits post intervention. Costs per targeted household, CHT_v, such as community assessments and water quality testing, were $18 and $14 (in 2010 US $) for the Enhanced and Basic variants respectively. Additional costs per adopting household, CHA_v, were $109 and $94 for the Enhanced and Basic variants respectively. These costs were mostly expenses associated with the infrastructure of the program (85% for Enhanced and 93% for Basic). Under a perfect compliance scenario, the difference between the cost-effectiveness of the Enhanced ($127) and Basic ($108) programs would have been $19. However, after accounting for compliance, we found a per-household cost-effectiveness difference of -$33 in achieving the Habit of drinking UV-safe water between the Enhanced ($208) and Basic ($241) variants during the first four months following the intervention.

Using the Compliance Framework (see Table 3.3) we calculated the cost-effectiveness of the secondary outcomes of the Enhanced (E) and Basic (B) variants for the Adoption (E=$132; B=$114), procurement Knowledge (E=$148; B=$140), consumption Knowledge (E=$208; B=$158), procurement Access (E=$141; B=$124), consumption Access (E=$174; B=$188), procurement Habit (E=$174; B=$160), and Exclusive consumption (E=$308; B=$300) components. By analyzing the evolution of compliance (see Figures 3.5 and 3.6), we also calculated the cost-effectiveness for the Habit of consuming UV-safe water during the first two months (E=$172; B=$195) and the eight-to-ten-month period (E=$292; B=$217) following the intervention.

5. Discussion

5.1 Compliance Framework

Research in development studies is often polarized along summative and formative approaches, resulting in a limited understanding of the mechanisms by which interventions work (Gertler et al. 2011; Rao and Woolcock 2003). Combining summative and formative approaches is particularly relevant for the HWTS sector because impacts rely on many behavior changes in the target population.

With the Safe Drinking Water Compliance Framework, we could select a primary outcome measurement to rigorously evaluate the extent to which a program affected behavior change, and also a series of secondary outcomes that provided useful information about its strengths and weaknesses. Deconstructing household compliance into its components (Adoption, Knowledge, Access, Habit, and Exclusive Use) makes it possible to identify specific program trends and potential modifications to increase compliance. By disaggregating the components further into procurement and consumption, the role of the user by age or gender can also be revealed (see (Ray 2007) There are certainly other factors that influence compliance, including economic status, social interactions, norms, and perceptions (Figueroa and Kincaid 2010; Mosler 2012), but many of these operate – and so can only be addressed -- beyond the household level.

5.2 User Compliance in Intervention and Control Periods

The Mesita Azul program had a significant impact on increasing the habit of consuming safe water, our primary outcome. In a review of 26 point-of use water treatment studies that focused on behavior change, seven showed high sustained use >50%, 13 showed a range of 1-34%, and five found initial use rates >50% followed by a notable decline (Parker Fiebelkorn et al. 2012). Three of the papers used the physical presence of intervention materials (equivalent to procurement Access in our Framework), 14 used some form of water quality testing (consumption Access), seven used self-reporting and one used structured observation (Parker Fiebelkorn et al. 2012). In comparison, by our relatively strict outcome of the habit of safe water consumption, the 50% compliance rate documented in our study is high. Increasing this habit from approximately 20% to 50% (Figure 3.3) of the targeted population is a considerable achievement in communities without working piped systems, a decade of failed promotion of boiling and in-home chlorination, and *garrafon*-bottled water in only one-fifth of households during baseline. The observed substitution effect, in which almost half of households with a *garrafon*-bottled water habit switched to UV-safe water as a habit, was evidence of the program's strengths. However, the intervention did not expand Exclusive Use (Consumption) to a majority of the targeted households.

Our Compliance Framework showed that post-intervention compliance was significantly higher than in the control periods. The Mesita Azul program was consistently superior to *garrafon*-bottled water across all procurement – but not all consumption -- measures. There could be several reasons for this. The presence of a UV system reduces the need to purchase *garrafon*-bottled water. But the Mesita and *garrafon*-bottled water used similar containers, and thus, once water has been procured, the barriers to consumption are similar. In addition, while the intervention sought to address barriers to procurement (e.g. fast disinfection process) and consumption (e.g. no change in the taste of water), most activities during outreach and installation were focused on procurement.

The downward trend in the compliance rate as the components shifted from adoption to the exclusive consumption of safe water is consistent with previous HWTS trials (Arnold et al. 2009; Luby et al. 2008). For the Mesita Azul program (which drove compliance during intervention periods), the drop in compliance was gradual and apparently multi-causal. Insufficient knowledge on how to procure safe water, or Mesita Azul relocation to an inconvenient site, contributed to a slight drop in procurement (see Figure 3.5). Limited knowledge of the negative effects of drinking untreated water reduced consumption but did not fully account for the significant drop between access to (consuming) safe water and its exclusive consumption. Knowledge of how a system works is never enough for sustained use as it is just one of many factors, such as social pressures or existing habits, that influence HWTS compliance (McLennan 2000; Moser and Mosler 2008; Mosler 2012; Wood et al. 2012).

In our study, the Mesita Azul program experienced proportionally less of a decline than *garrafon*-bottled water between adoption and the habit of procuring safe water, but a greater decline between rates of access to safe water and its exclusive consumption. This showed how an established water management practice (*garrafon*-bottled water), with a high procurement barrier, resulted in a narrower gap between access and exclusive consumption than a recently introduced alternative with a lower barrier to procurement. To improve compliance rates, recent studies have identified other social factors that drive uptake in different contexts (Juran and MacDonald 2014; Roma et al. 2014).

5.3 USER COMPLIANCE IN ENHANCED AND BASIC PROGRAM VARIANTS

Our results showed that the small modifications that were meant to reduce user barriers led to early improvements in compliance outcomes, supporting the arguments of behavioral economists that small changes can be both doable and effective (also Banerjee et al. 2011; Bertrand et al. 2006). Since the randomization of the Enhanced and Basic programs did not lead to fully equivalent groups, we adjusted our analysis for baseline imbalances in *garrafon*-bottled use, and still found the primary outcome to be significantly higher in Enhanced program communities between months zero and four. We also ran a comparison contingent on adoption of the UV system, which limits analysis to households with certain shared characteristics, and still found higher compliance rates in Access and Habit within Enhanced program communities.

Both program variants resulted in approximately the same Habit of consuming safe water (from UV disinfected and *garrafon*-bottled water) between months zero and four. This result could be driven by differences in group characteristics or pre-intervention safe water practices across both groups. Lower use of *garrafon*-bottled water in Enhanced communities at baseline could be an indication of higher barriers for any safe water practice. Alternatively, it could be that higher barriers to securing safe water in Enhanced communities were specific to *garrafon*-bottled water (e.g. distance to a vendor). This could mean that the observed difference across the two groups was the result only of differences in baseline drinking water practices.

The drop in compliance observed over time for the Enhanced program, but not for the Basic (see Figures 3.5 and 3.6), suggests that the barriers specific to procuring *garrafon*-bottled water were not the only reason for lower baseline safe water consumption in Enhanced communities. From (qualitative) informational interviews with program staff, it seemed that the main drivers of additional early compliance in the Enhanced variant were the money-back guarantee and the one-month follow-up visit. The guarantee allowed households with lower priority for safe water to gain access to it without having to assume risks or make binding payment commitments. Some of these households did not have the motivation or enabling conditions to face ongoing operation of the UV system and constant consumption of safe water. Studies have often shown a clear decline in use over time (Brown et al. 2009; Luby et al. 2008; McLennan 2000). The follow-up visit within one month of the Enhanced intervention might have postponed this effect; this visit could have also contributed to longer-term compliance by relocating the system to a more convenient area or by clarifying questions that were limiting compliance.

Based on our results and analysis, we conclude that there was a high likelihood that the Enhanced program led to higher compliance rates than the Basic program while the additional program components were active. Over time, the benefits of the Enhanced program disappeared. Future experiments testing the “small hassles” hypothesis should be designed to better understand whether small conveniences lead to big improvements in uptake mainly for one-time programs (such as signing up for a bank account) or also for programs that the user needs to sustain (such as drinking safe water daily). Future work with the Mesita Azul program specifically may benefit from pilot testing strategies outside the current HWTS paradigm, such as expanding a narrow focus on drinking water to making all domestic water safe to drink (as suggested by our observations of multiple water access points in the household) or switching from a product-based to a service delivery model.

6. CONCLUSIONS

Consistent and sustained use of HWTS systems (or user "compliance") remains one of the least understood features of safe water programs, and thus one of their least well-implemented steps. This chapter developed a Safe Drinking Water Compliance Framework in which compliance is disaggregated into Adoption, Access, Knowledge, Habit, and Exclusive Use. Deconstructing compliance into its components allows researchers and practitioners to identify, for any given safe water approach, the practices at which use falters, and which practices can feasibly be strengthened to encourage sustained use. We applied the framework to a UV-based HWTS program, the Mesita Azul, in rural Mexico; we found that UV program significantly improved compliance, where compliance was defined as the habit of consuming safe water. Half the commercial garrafon-bottled water users pre-intervention switched to UV disinfection post-intervention. We suggest that conceptualizing "compliance" as a multi-part phenomenon is both intellectually and practically useful for future HWTS research.

Behavioral research on poverty and health has argued that small programmatic changes to reduce hassles at the user end can lead to big improvements in uptake. The Mesita Azul program was tested in two variants: Basic and Enhanced (with additional user conveniences). We analyzed the compliance rates of each variant at each Framework component, and calculated the full costs of the program – from community assessment to post-installation follow up visits – per household targeted, and per household adopting. The Enhanced variant led to higher compliance while enhancements lasted; it was more cost-effective for Access and Habit formation. But compliance and cost-effectiveness degraded with time for our primary outcome, the habit of consuming safe water. It may be that small conveniences are more effective for one-time uptake programs than for programs that need sustained behavior changes.

Chapter 4. Field efficacy evaluation of an ultraviolet disinfection and safe storage system and assessment of post-treatment water quality risks.

1. INTRODUCTION

Household water treatment and safe storage (HWTS) is an important option for households whose drinking water sources do not meet microbiological water quality guidelines (Mintz et al. 1995; Rosa and Clasen 2010). Several studies have found that HWTS can reduce self-reported diarrhea outcomes (Arnold and Colford Jr 2007; Clasen et al. 2009; Fewtrell et al. 2005; Sobsey 2002). However, it remains a major challenge for HWTS programs to achieve higher adoption and consistent use rates (Brown and Clasen 2012; Clasen 2008; WHO and UNICEF 2012). Consistent use of existing options has been partly limited by the perceived negative taste of chlorine; the dependence on the constant acquisition of supplies of chlorine and coagulation products; and the relatively long wait times for treatment via solar disinfection, boiling, and certain filtration systems (Sobsey et al. 2008). From the user perspective, ultraviolet (UV) disinfection, where technologically feasible, may offer several advantages to other HWTS options because it is a fast process that does not require consumables and does not change the aesthetic characteristics of water.

Although UV disinfection is an established technology and has been shown to be effective both for centralized and point-of-use systems (Abbaszadegan et al. 1997; Colford et al. 2009; EPA 2006; Hijnen et al. 2006), there have been only a few evaluations of its effectiveness in developing country households (Brownell et al. 2008; Gruber et al. 2014b, 2013; Reygadas et al. 2007). Assessing the risk of post-treatment contamination is particularly important because UV treatment does not produce a residual disinfectant. Previous studies have documented that water quality can degrade during household storage (Kumpel and Nelson 2013; Levy et al. 2008; Wright et al. 2004).

We conducted a cluster-randomized trial to evaluate an HWTS program based on a UV disinfection and safe storage system. The research objectives were to (i) measure the field efficacy of the system in improving water quality (*E. coli* levels), (ii) assess the risk of post-treatment contamination, and (iii) develop a water quality model to better to understand household risk factors that drive recontamination. As part of this trial, we also measured the health and water quality impacts and the levels of adoption and consistent use achieved by the program. We have previously reported the population level impacts (program effectiveness) using an intention-to-treat analysis (Gruber et al. 2013) and complier average causal effect analysis (Gruber et al. 2014a) on drinking water quality and diarrheal prevalence.

2. BACKGROUND

2.1 STUDY SITE

We conducted our field trial in rural communities located in Baja California Sur, Mexico. Participating communities ranged from 8 to 31 households, with limited access to urban centers and basic services. Only 14% of households were connected to the grid, although 81% had solar panels (100 W_{peak}). The main economic activities included livestock ranching, small-scale farming, and fishing. Most households in participating communities relied on springs and shallow wells for their drinking water; 20% of the population regularly supplemented domestic supplies with *garrafon*-bottled water (reusable 20L bottles, filled with treated water by urban vendors). Locally-sourced water was commonly stored in wide-mouth containers (e.g., 200 L barrels, buckets, plastic water coolers, and *tinajas* -- traditional clay containers) (Gruber et al. 2013). Except for *garrafones*, and to some extent water coolers, water was typically extracted by dipping a cup into the storage container.

2.2 DESCRIPTION OF THE INTERVENTION

The Mesita Azul ("little blue table" in Spanish) safe water program was developed through a collaboration between UC Berkeley and Fundacion Cantaro Azul, a non-profit organization based in Mexico (Reygadas et al. 2009). The program consisted of an ultraviolet disinfection system (Mesita Azul), a 20 L narrow-necked container (*garrafon*) for storing treated water, and outreach activities (described below) intended to increase access to and consumption of safe water in rural households.

The Mesita Azul was designed to be a low-cost, easy-to-use, and attractive water treatment system for low-resource settings (Figure 4.1). It uses a low-pressure ultraviolet lamp (254 nm) to inactivate bacteria, viruses, and protozoa, without affecting the physicochemical characteristics of water (including temperature and taste). The system operates at flow rates of up to 5 L/min, allowing households to treat their daily water needs in less than five minutes. While in operation, the system consumes 20 W of electricity, equivalent to a small compact fluorescent lamp, and can be powered by solar panels or the grid.

The Mesita Azul was developed based on the UV Tube design principles (Brownell et al. 2008). Under standard conditions it delivers a germicidal fluence of $1,224 \pm 66$ J/m^2 (95% Confidence Interval), determined from biological assays using MS2 coliphage and following Section 6.3 of the NSF/ANSI Standard 55 as a microbiological performance test model (NSF 2002). This dose meets the WHO's "highly protective" microbial performance target for household water treatment (WHO 2011a) and exceeds by three times most other UV disinfection standards (DVGW 2006; NSF 2002; ÖNORM 2001). The high design dose allows the system to maintain its germicidal effectiveness throughout the lamp's lifetime and for water with absorbance up to 0.1 cm^{-1}.

The Mesita Azul program, implemented by Cantaro Azul, included: a needs assessment, a community presentation, enrollment of program participants, household installation of UV systems, training of household members to operate and provide basic maintenance to the UV system, training of several technicians in each community to carry out system repairs, and a follow up visit to support technicians and households that reported any problems in using the system. During the needs assessment, Cantaro Azul staff tested the water in each community for arsenic, nitrates, total dissolved solids, and absorbance (at 254nm). The program was rolled out in communities whose drinking water was at microbiological risk but did not contain other contaminants that could hamper its performance (absorbance $<0.1\ \mathrm{cm}^{-1}$) or that could not be addressed by UV treatment. To enroll in the program households had to make a one-time payment of USD$20 (MXN$250) or commit to pay $24 (MXN$300) in installments over a six-month period. For the purposes of this study, we defined compliance with the Mesita Azul program as households that, after enrollment, had UV treated and safely-stored water present during an evaluation visit.

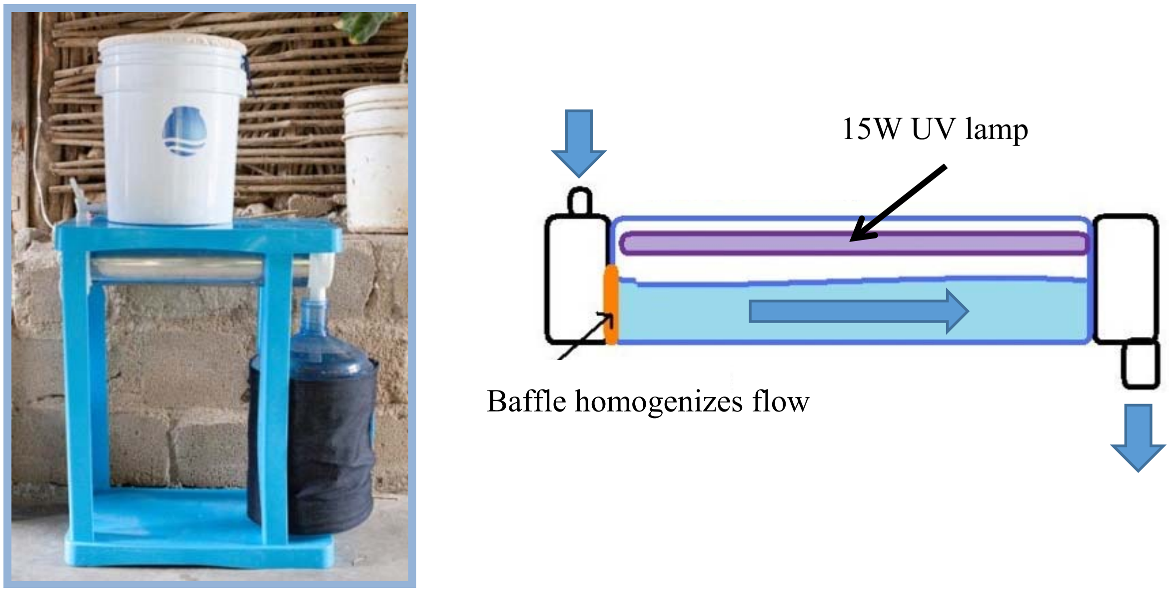

Figure 4.1: Image of the Mesita Azul and schematic of its disinfection chamber.

3. MATERIALS AND METHODS

3.1 STUDY DESIGN

Our research team conducted a cluster-randomized stepped wedge trial to evaluate the Mesita Azul as it was rolled out to 444 households located in 24 rural communities (Gruber et al. 2013). The trial lasted 18 months. At baseline, we randomized the sequence of program rollout at the community level, which balanced covariates between control and intervention periods and created two comparable groups (Brown and Lilford 2006; Hussey and Hughes 2007). All communities started in the control group, and, at each "step", households in four new communities crossed-over to the intervention group (Figure 4.2). Cantaro Azul staff carried out the community meetings and UV system installations during the step in which clusters crossed-over to the intervention group. Our evaluation team visited all communities to measure outcomes at baseline and during each subsequent step. By the end of step six, Cantaro Azul had rolled out the program to all 24 communities and the evaluation team had visited each cluster seven times.

We registered this study at ClinicalTrials.gov (NCT01637389), the Office for the Protection of Human Subjects at the University of California, Berkeley approved all research protocols (CPHS 2009-1-47), and all participating households provided informed consent.

Clusters	Baseline	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
1-4	0	X 0	0	0	0	0	0
5-8	0	0	X 0	0	0	0	0
9-12	0	0	0	X 0	0	0	0
13-16	0	0	0	0	X 0	0	0
17-20	0	0	0	0	0	X 0	0
21-24	0	0	0	0	0	0	X 0

0 = Observation

X = Intervention

Figure 4.2: Study Design: cluster randomized stepped wedge trial.

3.2 GENERAL DATA AND SAMPLE COLLECTION PROCEDURES

In each survey visit, we collected data on the demographics, socioeconomic characteristics, and health status of household members. We also documented household hygiene conditions and water management practices (source type, access points characteristics, and treatment processes -- if any). In post-intervention visits, we recorded user interactions with the UV system and checked system functionality.

In all household visits, we asked interviewees to identify all water access points in the home that had been used for drinking purposes by any household member in the past seven days. When only one was reported, we asked interviewees to identify an alternative point of access from which they would consume if their preferred access point was not available. We then requested interviewees to provide us with water from each of the identified points of access as though they were getting a drink (typically in a glass or a cup), from which we collected samples for analysis in 100 mL sterile containers. This approach allowed us to assess the quality of water immediately before ingestion.

3.3 SAMPLE ANALYSIS

We used the concentration of *E. coli* as an indicator of fecal contamination (Tallon et al. 2005). We stored sample bottles in hermetically sealed containers inside a cooler with water and ice for up to 12 hours. Samples were processed using IDEXX (Westbrook, ME, USA) Colilert 18 and Quanti-Tray 200 products. We incubated trays for 18 to 24 hours at 36°C (±4 °C) and determined the most probable number (MPN) of *E. coli* using the manufacturer's table (detection range of 1-200 MPN/100 mL). To maintain and verify quality control, we collected duplicates and blanks (samples from bottles with sterile water filled at households and the field lab) for 10% of the samples.

3.4 DATA ANALYSIS

To compare the risk of contamination between different water management practices and to develop our household level water quality model, we converted *E. coli* concentration to a binary outcome: presence-absence. This decision was motivated by World Health Organization (WHO) recommendations that safe drinking water contain no detectable *E. coli* in a 100 mL sample, and the limited evidence for an increased risk of diarrhea beyond the one *E. coli*/100 mL cutoff (Gruber et al. 2014b; WHO 2011c). To carry out more detailed comparisons across water management practices, we used a priority assessment classification based on the observed *E. coli* concentration (MPN counts/100 mL): Low Risk [0,1); Intermediate Risk [1,10); High Risk [10,100); and Very High Risk (≥100) (WHO 2011b).

All data analyses were conducted using Stata 12 (Stata Corp, College Station, TX, USA).

3.5 FIELD EFFICACY EVALUATION

3.5.1 CONTROLLED COMPARISON TESTS

Household drinking water quality can be influenced by multiple factors internal and external to the Mesita Azul system, including: water source characteristics, seasonality of environmental conditions, water handling practices, hygiene and sanitation conditions, a household's awareness of the relationship between water and health, and operation and performance of the UV system. To isolate and evaluate the field efficacy of the Mesita Azul, we used an as-treated analysis, in which we defined treated households as those that complied with proper usage of the Mesita Azul as promoted by the safe water program. Specifically, compliance was defined as households having UV-treated water (based on self-report) safely stored in a *garrafon* (based on visual observation) during an unannounced evaluation visit; for this analysis we do not consider "compliance" with other treatment strategies. To address biases that can result from the as-treated analysis (Friedman et al. 1998), we developed a robust assessment based on three types of controlled comparisons. For these analyses, we used samples collected exclusively from drinking glasses.

Intervention vs. Control: We compared drinking water quality between complying households in intervention periods and households in control periods that would later acquire a UV system. Comparing the compliers in the intervention group to the entire control group could introduce a bias due to presence of non-compliers in the control group. The stepped wedge design allowed us to identify likely compliers in control periods based on observed behavior after crossover to the intervention periods (Gruber 2014). We computed risk differences and confidence intervals using a chi-square test (χ^2).

Intervention vs. Pre-Intervention: We compared drinking water quality pre- and post-intervention. We restricted this analysis to complying households during the step at which the intervention was introduced and compare water quality to those same households one step prior to the intervention; we only include households that had data available from both steps. The seasonal variation of water quality could introduce a time bias in this comparison. For this analysis, we calculated risk differences and confidence intervals using the McNemar test, which does not require assumptions regarding independent observations (McNemar 1947).

Intervention vs. Alternative: We compared the quality of drinking water treated with the UV system and stored in a *garrafon* to that of drinking water from alternative access points available in the household. We selected the alternative access point by asking the interviewee from where she would drink if she did not have UV treated water available. By collecting two samples from the same location at the same point in time, we were able to control for seasonal effects. However, we recognized that alternative water sources might be managed differently once the household had access to UV-treated water stored in a *garrafon*. We used the McNemar test to calculate risk differences and confidence intervals.

3.5.2 COMPARISON TO OTHER TREATMENT AND STORAGE ALTERNATIVES

We carried out comparisons of the presence of *E. coli* in drinking water treated with the UV system and stored in *garrafones* to other treatment and storage practices. These alternatives were: *garrafon*-bottled water purchased from urban vendors, in-home chlorination, boiling, and storing UV treated water in containers other than *garrafones*. In these comparisons we pooled samples collected throughout the study from both intervention and control groups for each water management practice.

3.5.3 SAFE DRINKING WATER RELIABILITY FRAMEWORK

According to Quantitative Microbiological Risk Assessment model estimates, even sporadic consumption of contaminated water can erase most of the potential health benefits associated with potable water interventions (Brown and Clasen 2012; Enger et al. 2013b; Hunter et al. 2009). To consistently drink safe water, people need to consume water from access points that are reliable. We created a framework to assess safe drinking water reliability and used it to compare UV disinfection and safe storage with non-UV access points and with *garrafon*-bottled water. For a given water management practice, we pooled multiple samples collected at different points in time for each household and computed the proportion of samples that had non-detectable levels of *E. coli*. We only used samples collected from drinking glasses. We restricted our analysis to households that had at least three samples collected throughout the study from the same water practice. We categorized the degree of reliability of a water practice by the proportion of samples with non-detects (*E. coli* was absent) for each household: Always Safe (100%); Mostly Safe (99%, 66%); Often Contaminated (65%, 34%); Mostly Contaminated (33%, 1%); Always Contaminated (0%). Then, we used these conditions to create graphs depicting the percentage of households per level of reliability for each water management practice.

3.6 POST-TREATMENT WATER QUALITY ASSESSMENT

3.6.1 WATER QUALITY AT THE OUTLET, STORAGE CONTAINER, AND DRINKING CUP

We assessed the quality of water at different steps of the UV treatment and safe storage practice, by aggregating samples collected from the outlet of the UV system (during the second post-intervention visit), directly from *garrafones* with UV treated water (during visits when there was a second *garrafon* available), and drinking glasses filled from *garrafones* with UV treated water (in complying households throughout intervention periods).

We also carried out two controlled tests that allowed us to reduce biases that could have arisen from aggregating samples collected from different households and at different points in time. During the second post-intervention visits, we collected matched samples from a drinking glass and the outlet of the UV system. Following our study protocol, we first collected a sample from a drinking glass filled with UV treated water stored in a *garrafon*. Then we asked the interviewee to fill a *garrafon* using the UV system and we collected the first 100 mL that exited from the outlet. During baseline, we collected matched samples directly from storage containers used for drinking purposes and from glasses filled from such containers. We asked interviewees to pour water from a storage container into a 100 mL sterile recipient in the same way that they would fill a drinking glass in preparation for drinking (e.g., opening a spigot, using a pump, or titling the container to extract water from its top). We then collected a second, “matched” sample from the drinking glass (see Section 3.3 above). We obtained matched data for all the households that met these conditions and carried out McNemar tests to calculate risk differences and their 95% confidence intervals.

These comparisons allowed us to isolate the impact of storage and the use of a glass on the quality of drinking water.

3.6.2 POST-TREATMENT WATER QUALITY PROCESS MODEL

We developed a logistic regression model of post-treatment *E. coli* contamination based on a series of explanatory variables that represent processes and conditions associated with managing water treated with the UV system and stored in *garrafones* (see Table 4.1). We used the presence or absence of *E. coli* (in 100 mL) as the outcome variable. We controlled for time (fixed effect for evaluation step) and used a robust estimator of variance to compute the contamination odds ratios and their 95% confidence intervals for each of the explanatory variables. We limited the model to samples collected (directly or via a drinking glass) from *garrafones* with UV treated water.

Practices that could modulate contamination levels while using the Mesita Azul included water treatment, water storage, storage container washing, and extraction from the storage container; conditions include the environment and human hygiene (Figure 4.3). These practices and conditions were directly related to water management; thus the results of the model could be used to improve the Mesita Azul program and inform the development of more effective HWTS interventions. In contrast, many household water quality models are based on explanatory variables that are less viable for water programs to act upon, such as employment, income, gender, education, or age of household members. In Table 4.1 we present our hypothesized effects on contamination for each process and condition, their respective explanatory variables, operational definitions, and types of data collected.

Table 4.1: Origin and structure of explanatory variables used in household water quality model.

Water Management Processes and Conditions	Potential Effect on Contamination Level	Explanatory Variable	Operational Definition	Type of Collected Data
Washing	Using untreated source water could introduce contamination to container.	Type of water used for washing storage container.	Used disinfected water last time they washed container?	Reported; Binary
	Using cleaning supplies could reduce contamination.	Type of cleaning supplies used for washing storage container.	Used bleach or soap last time they washed container?	Reported; Binary
Treatment	Working system should reduce contamination.	Operational status of the system.	Does the UV system work at time of visit?	Observed; Binary
	Operating the system correctly should reduce contamination.	Ability of operator to use system.	Is the operator an expert? (Knows the operation steps in perfect order and carries them out with confidence.)	Observed; Binary
Storage	Storage time could modulate contamination via environmental exposure and bacterial growth or decay.	Length of time that water has been in storage container since it was last filled.	Time since container was last filled.	Reported; Continuous (Time unit = 1 day; range from 0 to 30.)
	Exposure to the environment during storage could increase contamination.	Type of exposure of stored water to the environment.	Is container covered with proper lid at time of visit?	Observed; Binary

Water Management Processes and Conditions	Potential Effect on Contamination Level	Explanatory Variable	Operational Definition	Type of Collected Data
Extraction	Extractions from storage container could increase contamination.	Number of water extractions since storage container was last filled.	Number of extractions (in multiples of 10) since container was last filled. (Calculated based on remaining volume, assuming container was filled to top.)	Observed; Continuous (Each extraction = 400 mL; range from 0 to 50.)
	The contamination risk during the extraction process could vary across different extraction methods.	Type of mechanism used to extract water from storage container.	Extraction with pump? Extraction through spigot? (In contrast with tilting container and pouring water directly from it.)	Observed; Categorical
	Pouring extracted water into drinking glass could increase contamination.	Point at which sample is collected during the extraction process.	Is sample collected from drinking glass? (As opposed to directly from extraction mechanism.)	Observed; Binary
Hygiene	The overall infrastructure of the house could modulate contamination risks.	Type of household infrastructure.	Does household have walls and concrete floors?	Observed; Binary
	The hygiene of the kitchen could modulate contamination risks.	Level of kitchen hygiene.	Are the kitchen hygiene conditions good or very good? (Evaluated based on presence of flies, trash, and exposed food.)	Observed; Binary
	The hygiene of people in the house could modulate contamination.	Type of infrastructure available for hand washing.	Is there a water access point used mainly for hand washing?	Observed; Binary

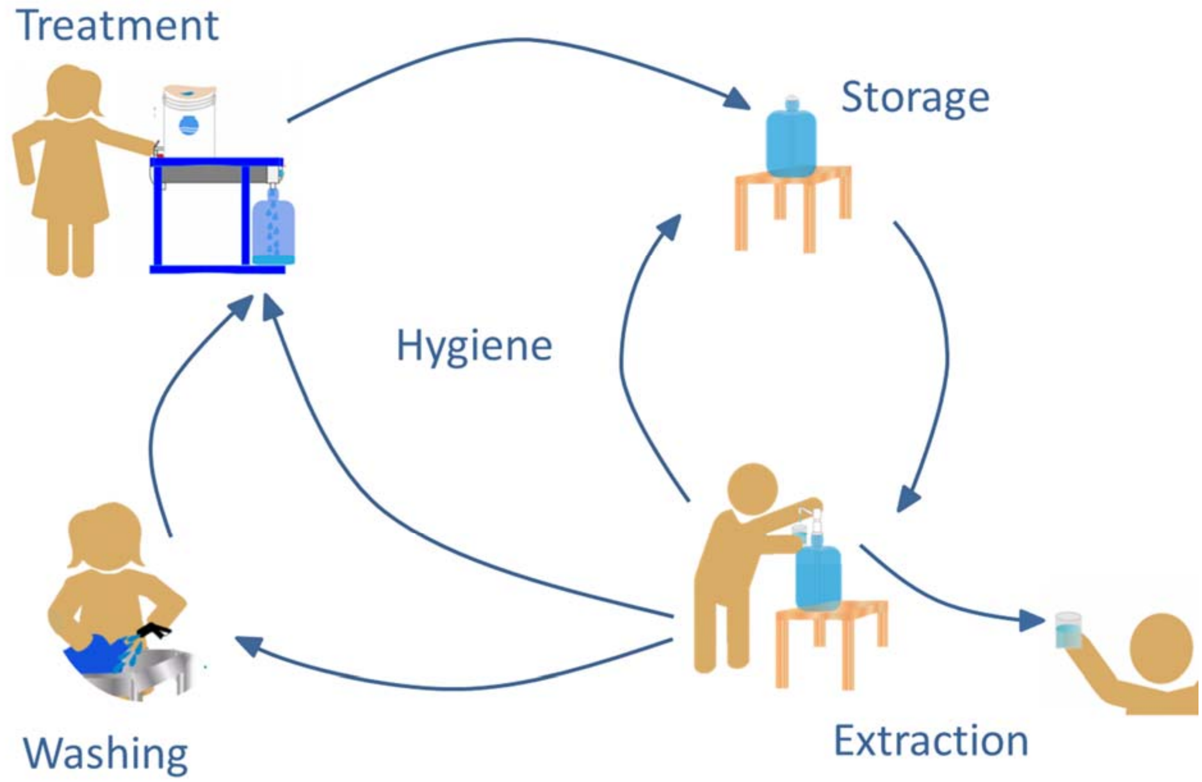

Figure 4.3: Post-treatment water quality model based on household water management processes and conditions.

4. RESULTS

4.1 FIELD EFFICACY EVALUATION

4.1.1 CONTROLLED COMPARISON TESTS

We found that treating water with the UV system and storing it in *garrafones* resulted in significant improvements in the quality of drinking water (Figure 4.4). The risk difference was calculated for each comparison group based on the proportion of samples with *E. coli* ≥ 1 MPN/100 mL.

Intervention vs. Control: We identified 449 intervention and 542 control household observations (Figure 4.4) for this analysis. We observed a risk difference of -28.0% (CI: -33.9%, -22.1%; χ^2) in the presence of *E. coli* between samples collected from drinking glasses filled from *garrafones* with UV treated water (Mesita Azul compliers: 29.4%; N=449) compared to control households that would later become compliers after crossing over to the intervention arm (57.4%; N=542). Control samples were collected from drinking glasses filled from preferred access points: 79% no treatment, 20% *garrafon*-bottled water, <1% boiling and chlorination.

Post-intervention vs. Pre-intervention: 140 household observations (Figure 4.4) were included in this analysis. We observed a risk difference of -38.6% (CI: -48.9%, -28.2%; McNemar) between samples matched by household and collected from drinking glasses filled from garrafones with UV treated water during the step the intervention was implemented (24.3%; N=140) and samples collected from drinking glasses filled from preferred access points during the step prior to the implementation of the intervention (62.9%; N=140).

Intervention vs. Alternative: 224 household observations met the criteria for this analysis (Figure 4.4). We observed a risk difference of -37.1% (CI: -45.2%, -28.9%; McNemar) between samples matched by household, comparing samples collected from drinking glasses filled from garrafones with UV treated water (25.9%; N=224) to samples collected during the same visit from drinking glasses filled from alternative access points (62.9%; N=224).

After classifying samples into four risk categories based on MPN *E. coli*/100 ml (Low Risk [0); Intermediate Risk [1,10); High Risk [11,100); and Very High Risk (≥100)), we observed that water quality improvements post-intervention were mostly driven by reductions in the frequency of water in the High and Very High Risk categories across all three analyses (Figure 4.4). We report the proportions of contamination between intervention (I) and control (C) samples, as well as their relative risks (RR) for the Intermediate Risk (I: 0.21; C: 0.26; RR: 0.82), High Risk (I: 0.05; C: 0.19; RR: 0.27), and Very High Risk (I: 0.03; C: 0.13; RR: 0.24) levels. The trends were similar for the Post- versus Pre-intervention and the Intervention versus Alternative comparisons.

4.1.2 COMPARISON TO OTHER TREATMENT AND STORAGE ALTERNATIVES

We compared sample contamination from households that complied with Mesita Azul procedures to those that drank water collected from other treatment alternatives: commercial *garrafon*-bottled water, in-home chlorination, and boiling. We collected all samples from drinking glasses. We found no difference in water quality when comparing samples taken from access points that complied with the Mesita Azul instructions (25.9%; N=624) and samples from purchased *garrafon*-bottled water (24.0%; N=387): RD 1.9 (CI: -3.5%, 7.4%; χ^2). We repeated this comparison using *garrafon*-bottled water samples collected only from households that acquired a UV system later in the study and found a similar result. We observed a non-statistically significant risk difference of -9.9% (CI: -25.4%, 5.5%; χ^2) between samples from Mesita Azul compliers (26.0%; N=624) and chlorination or boiling (35.9%; N=39). In contrast to these alternatives, samples collected from un-treated access points used for drinking were more likely to test positive for *E. coli* (63.7%; N=1,781) (Figure 4.5).

To minimize risks of post-treatment contamination, program staff strongly encouraged people to store UV treated water in *garrafones* only. However, 40% (N=286) of households stored UV treated water in other types of containers at least once during the study. Such containers included *tinajas* (traditional clay or rock containers), buckets, and plastic water coolers. We observed a risk difference of -21.8% (CI: 14.3%, 29.2%; χ^2) between UV treated samples stored in *garrafones* (26.0%; N=624) compared to storage in alternative containers (47.7%; N=220).

	Intervention vs Control		Pre-Intervention vs Post-Intervention		Disinfected vs Alternative	
	Control	MA	Before	After	Alternative	MA
Observations	542	449	140	140	224	224
Proportion of EC ≥ 1	0.57	0.29	0.63	0.24	0.63	0.26
Analysis	Chi-Squared Test Risk Difference (95%CI)		McNemar's Test for Paired Data Risk Difference (95%CI)		McNemar's Test for Paired Data Risk Difference (95%CI)	
Result	-0.28 (-0.34, -0.22)		-0.39 (-0.28, -0.49)		-0.37 (-0.29, -0.45)	

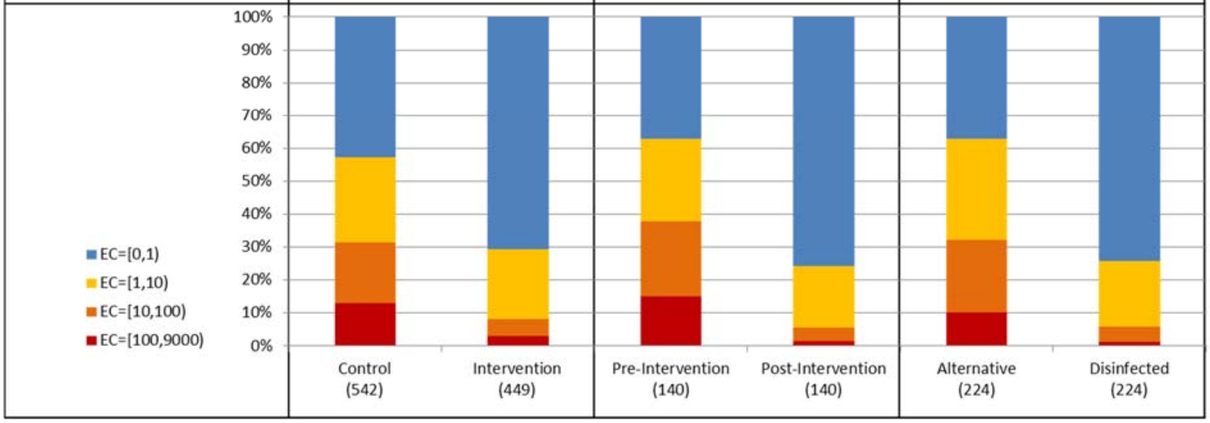

Figure 4.4: Risk difference and E. coli risk levels for the controlled comparison tests.

4.1.3 SAFE DRINKING WATER RELIABILITY FRAMEWORK

We assessed the reliability of water quality for the most prevalent water management practices observed during our study. For households that had at least three samples, collected at different times of the study, from drinking cups filled from *garrafones* with UV treated water, we found that 37% of households met the Always Safe category, 3% the Always Contaminated, and the remaining 60% had both *E. coli* positive and negative samples (Figure 4.6a). Ninety-seven households met this condition (45% had three samples; 31% had four samples; 24% had five samples). In contrast, for households that had at least three samples from cups filled from non-UV treated access points, 13% met the Always Safe category, 22% the Always Contaminated, and the remaining 75% had both positive and negative samples (Figure 4.6b). 171 households met this condition (31% had three samples; 32% had four samples; 37% had five samples). Restricting to non-UV treated samples collected only during control periods among households that later adopted the UV system led to similar results. The reliability of the UV treated water stored in *garrafones* and that of commercially purchased *garrafon*-bottled water was equivalent (Figure 4.6c).

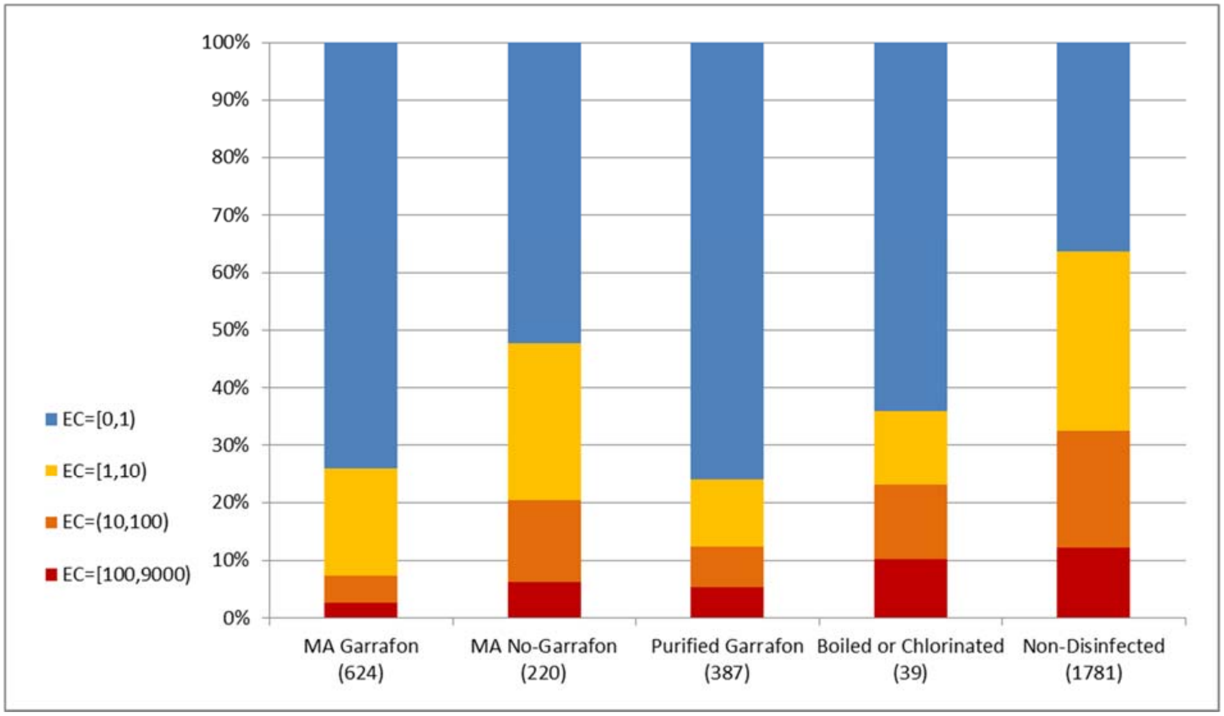

Figure 4.5: Fraction of E. coli samples in each risk category for water collected in drinking cups from different water sources. Number of samples is provided in parentheses.

4.2 POST-TREATMENT WATER QUALITY ASSESSMENT

4.2.1 WATER QUALITY AT THE OUTLET, STORAGE CONTAINER, AND DRINKING CUP

After aggregating data on UV treated water throughout the entire study, we observed *E. coli* in 5.0% of samples (N=161) collected directly from the outlet of the UV system; 21.1% (N=76) from storage containers (*garrafones*) filled with UV treated water; and 26.0% (N=624) from drinking cups filled from *garrafones* filled with UV treated water (Figure 4.7).

During the second post-intervention visit, we observed an increased risk *E. coli* contamination between samples collected from a drinking glass (19.5%; N=118) compared to matched samples from the outlet of the Mesita Azul (3.4%; N=118; RD 16.1%, 95% CI: 8.2%, 24.0%, McNemar).

To put these results in context, we can compare the results for UV-treated water with samples collected during baseline, before UV treatment was available to the households. Matched samples were collected directly from storage containers and from drinking glasses filled with water from the same containers. Most of the containers had been filled with disinfected water (67%) and had safe-storage characteristics (82%). The additional contamination that occurred at the drinking glasses was mostly driven by an increase in the proportion of samples with an Intermediate Risk level of *E. coli*, as can be observed by computing the relative risks for the Intermediate Risk (1.60), High Risk (1.00), and Very High Risk (1.10) concentration categories. Restricting the analysis to only *garrafon*-bottled water (N=64) resulted in the same effect (data not shown). We also observed the same trend in a smaller number of paired samples collected directly and through a drinking glass from *garrafones* with UV treated water during intervention periods (data not shown).

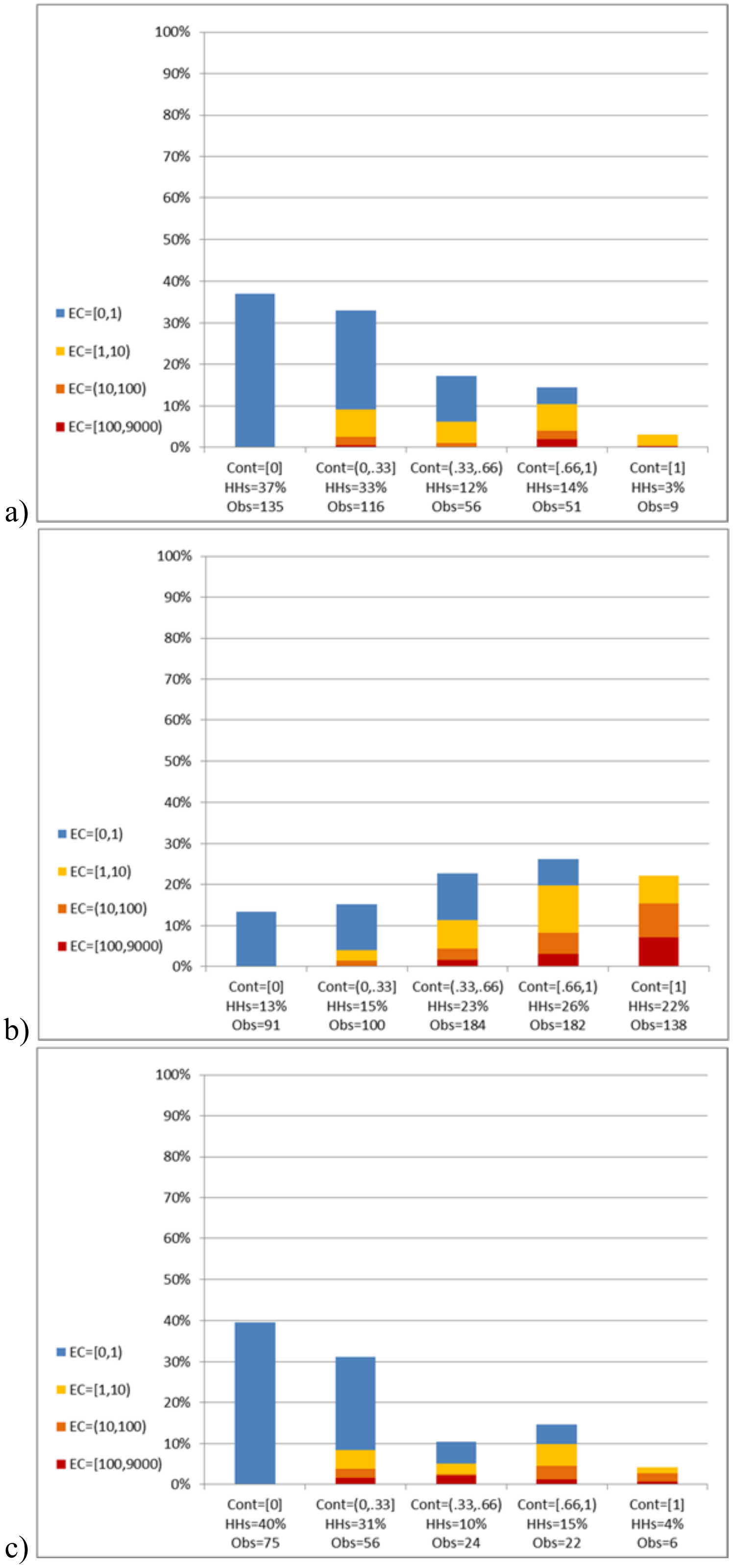

Figure 4.6: Water Quality Reliability Mesita Azul and Non-Mesita Azul.

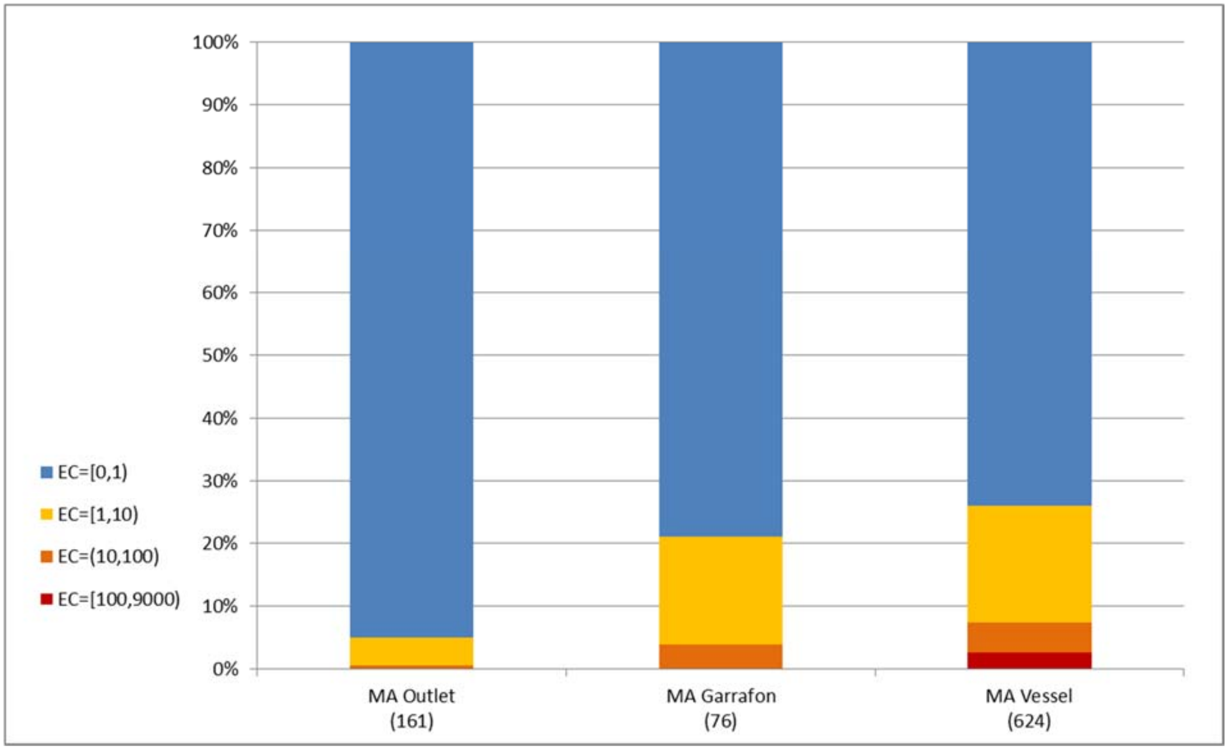

Figure 4.7: Fraction of E. coli samples in each risk category for water collected directly from the outlet of the UV system, from storage containers filled with UV-treated water, and from drinking cups filled from storage containers filled with UV-treated

4.2.2 POST-TREATMENT WATER QUALITY PROCESS MODEL

We present the results of our water quality model in Table 4.2. None of the Washing practices (using raw versus disinfected water and using plain water versus chlorine or soap to wash the *garrafon*) had statistically significant associations with the presence of *E. coli* in water. Both Treatment process variables resulted in significant reductions in contamination, with 74% lower odds for having a Mesita Azul in a working condition (odds ratio (OR)=0.26; CI: 0.10, 0.68) and 39% lower odds for having a skilled system operator as member of the household (OR=0.61; CI: 0.37, 1.00). For Storage, storage-time had a significant protective effect on contamination; each additional day since the container had been last filled reduced the odds of contamination by 19% (OR=0.81; CI: 0.70, 0.93). Having the storage container covered appeared to have a protective effect on contamination, but was not significant; however, only 2% of the observed containers were not covered. Of the Extraction variables, the number of extractions and the use of a drinking glass were significantly associated with contamination; each additional 10 servings (400 mL) extracted from the *garrafon* reduced the odds of contamination by 16% (OR=0.84; CI: 0.72, 0.98). The extraction method was not significantly associated with contamination. Samples that were collected via a drinking glass had increased odds of contamination compared to samples collected directly from the container (OR=1.91; CI: 1.02, 3.57). Among Hygiene variables, household infrastructure had a significant association with the presence of *E. coli* in the drinking glass; households with walls and concrete floors had lower 64% lower odds of contamination (OR=0.36; CI: 0.20, 0.65). Kitchen hygiene and access to a hand washing station were not significantly associated with contamination.

Table 4.2: Results from post-treatment water quality process model. Variables that had statistically significant association with the presence of E. coli in water are shown in bold.

Water Management Processes & Conditions	Independent Variables	% of 619 Observations	Odds Ratios	Confidence Intervals (95%)	
Washing	Used disinfected water last time they washed container?	18%	1.26	0.78	2.03
	Used bleach or soap last time they washed container?	62%	1.32	0.88	1.98
Treatment	**Does the UV system work at time of visit?**	**97%**	**0.26**	**0.10**	**0.68**
	Is the operator an expert?	**29%**	**0.61**	**0.37**	**1.00**
Storage	**Time since container was last filled.**	**<3d=68%**	**0.81**	**0.70**	**0.93**
	Is container covered with proper lid at time of visit?	98%	0.53	0.15	1.93
Extraction	**Number of extractions (in multiples of 10) since container was last filled.**	**≥10L=62%**	**0.84**	**0.72**	**0.98**
	Extraction with pump vs. tilting container?	50%	0.88	0.56	1.37
	Extraction with spigot vs. tilting container?	43%	1.43	0.65	3.11
	Is sample collected from drinking glass?	**85%**	**1.91**	**1.02**	**3.57**
Hygiene	**Does household have walls and concrete floors?**	**88%**	**0.36**	**0.20**	**0.65**
	Are the kitchen hygiene conditions good or very good?	86%	0.86	0.49	1.50
	Is there a water access point used mainly for hand washing?	20%	1.38	0.82	2.33

5. DISCUSSION

Through this field efficacy study we measured the impact of the Mesita Azul system on the microbiological quality of drinking water (presence of *E. coli*) among households that complied with the treatment and storage instructions (UV-treated water safely stored in a *garrafon* at the time of a survey visit). Complementing our previous evaluation of the Mesita Azul program as a whole (Gruber et al 2013), this as-treated analysis allowed us to estimate the maximum potential efficacy of the system. Since an as-treated analysis can introduce selection biases, we carried out a series of comparison tests to maximize the internal validity of the study and to develop a more robust impact assessment. We built on the results of the as-treated analysis to develop a post-treatment water quality model of household risk factors for *E. coli* contamination, including practices such as: storage, treatment, washing, extraction and household hygiene.

5.1 CONTROLLED COMPARISONS

We found evidence that the Mesita Azul system significantly reduced the presence of *E. coli* in drinking water among complying households. The risk differences observed in our three comparison tests were -28.0% (Intervention vs. Control), -38.6% (Post-Intervention vs. Pre-Intervention), and -37.1% (Intervention vs. Alternative). This is in contrast to our previous effectiveness evaluation, in which we reported a risk difference of -19% (intention-to-treat analyses) (Gruber et al. 2013). The observed additional benefits of compliance justify investments to increase program adoption and consistent use of the UV system. Further analysis to compare differences in the concentration of *E. coli* (as opposed to just presence-absence) revealed that water quality improvements were mostly driven by reductions in High and Very High Risk drinking water.

Even though compliance with the Mesita Azul led to significant reductions in *E. coli*, we still found that 24.3-29.4% of samples collected from drinking glasses filled with water treated with the UV system and stored in a *garrafon* had detectable levels of *E. coli*. In comparison, Levy et al. (2014) found in a field effectiveness evaluation that 48.8-61.3% of samples collected from storage containers with water that had been chlorinated by users had detectable levels of *E. coli;* we would expect chlorination to reduce contamination levels in stored water, compared to UV, due to its residual disinfection capacity. It is possible that the difference in results could be explained by water quality coming from the source; *E. coli* in source water was more prevalent in their study (87.8-93.5% positive for *E. coli*) than ours (57.4-62.9%) and that they collected samples directly from storage containers and we collected them via drinking glasses that were shown to increase the risk of contamination. The results from the UV system are encouraging; however, results are generalizable to only households that would comply with the Mesita Azul in similar contexts, due to the as-treated analysis.

5.2 COMPARISON TO OTHER TREATMENT AND STORAGE ALTERNATIVES

The Mesita Azul allowed complying households to produce drinking water of equivalent quality (defined as *E. coli* levels in water collected from drinking cups filled from storage containers) to that of purchased *garrafon*-bottled water. These results provide evidence that transferring the treatment responsibility from commercial bottling facilities in urban areas to individuals in rural households did not lead to an increase in *E. coli* contamination of drinking water; however, our results also suggest that storage in a *garrafon* is an important determinant of water quality, and has implications for Mesita Azul promotion.

Household chlorination and boiling were rare in the study area and, in most cases, water treated by these methods was stored in unsafe containers. This likely explains the higher proportion (but not statistically significant) of contaminated samples when comparing chlorinated and boiled water to UV-treated water stored in *garrafones*. We found evidence that storing UV treated water in *garrafones* reduced *E. coli* levels compared to other commonly used containers (*tinajas*, buckets, and plastic coolers). Our results reiterate that water treatment programs, including boiling and filtration, should emphasize the fecal contamination risks of storing water in containers that are not covered, have a wide opening, or require dipping a cup for extraction. Although Cantaro Azul staff worked hard to emphasize the importance of storing treated water in *garrafones*, 40% of households stored UV treated water in other types of containers at least once during the study. The Mesita Azul program should incorporate more effective behavior change strategies, including developing evidence-based messages using the results of this study to promote safe storage practices.

5.3 WATER QUALITY RELIABILITY

Drinking safe water consistently within a households depends on the reliability of water quality at each access point. Based on *E. coli* levels, compliance with the Mesita Azul system allowed users to have more reliable access to safe drinking water compared to all other water management practices observed in our study. Despite the importance of assessing reliability of HWTS strategies, it is difficult to implement because it requires collecting multiple samples from the same households over time. We encourage monitoring programs to incorporate a reliability index similar to that used in our study; more research is also needed to further develop measured of reliability. Note that it is necessary to collect at least two samples per household, because if only a single sample is collected the household will fall either in the "always safe" or "always contaminated" category, which may not be representative. It is also important to collect similar numbers of samples from each household for all water management strategies that are being evaluated. We found the reliability distribution to be relatively stable across households with three to seven samples each.

5.4 POST-TREATMENT WATER QUALITY ASSESSMENT AND MODEL

We observed an increase in the concentration of *E. coli* throughout the different phases of the UV treatment and safe storage process, from treating water with the UV system, storing it a narrow-necked container, and using a glass for drinking purposes. The largest increase in contamination occurred during the storage phase.

Considering the high germicidal dose delivered by the Mesita Azul UV chamber and the low absorbance of source water documented in study communities, we assume that *E. coli* was reduced to below the detection limit when users operated the system correctly. We suspect that most of the contamination events (5% of samples collected directly from the outlet) were due to: systems that were not working, improper operation, or contamination of the outlet itself. These assumptions are supported by the results of our model, in which we found statistically significant associations between the presence of *E. coli* in drinking cups and the state of the system and the ability of the operator. Based on these findings, the Mesita Azul program should revise its strategies to proactively identify failing systems and provide technical support, although there is not much room for improvement because already 97% of systems were working properly. In contrast, only 29% of operators could perform the operation steps in perfect order and carried them out with confidence when observed. Thus, we recommended that the Mesita Azul program strengthen its operator training strategy and considers identifying those that require further assistance. It is important to mention that operator's competence could be associated indirectly with other conditions that might also affect water quality.

Contrary to what we expected, additional storage time and number of extractions resulted in a statistically significant protective effect on the presence of *E. coli* in drinking water. Bacterial die off and limited growth inside the *garrafon* could explain the observed negative association with storage time. Bacterial settling could explain the negative association with extractions, as pumps and spigots extract water from the bottom of the *garrafon*, potentially reducing the number of *E.*

coli remaining in the garrafon over time. Based on our results, storing treated water for up to a week would not seem to pose additional contamination risks.

We found no significant association between *garrafon* washing practices and the presence of *E. coli* in drinking water. This was a surprising finding considering that less than 20% of households reported washing garrafones with disinfected water and that approximately 60% of untreated water was contaminated with *E. coli*. However, it is likely that the mixing of the small volume of untreated water leftover from the washing process with the large volume of disinfected water when filling the *garrafon* resulted in a high dilution rate that diminished the potential impact of washing practices on detectable *E. coli* concentrations in stored drinking water. It is important to point out that not finding an association in our study does not mean that it is safe to wash containers with untreated water, given that *E. coli* is only an indicator of contamination, that some pathogens have low infectious doses, and that some untreated water could be highly contaminated.

Improved household infrastructure conditions, particularly the presence of walls and concrete floors, were associated with lower water contamination rates. Safe water programs should also seek to partner with household infrastructure programs. Additional research is necessary to better understand how the hygiene directly affects the water quality in the *garrafones* and drinking glasses and thus contribute to developing more specific recommendations.

We found evidence of contamination introduced at the drinking glass through direct comparisons and also through a statistically significant association in the post-treatment process model. Contamination at the drinking glass could come from: water previously served into the glass or used to wash it; contact with soil or dirt; settling of dust into the glass; or contact with fomites. Contamination at the drinking glass affects most water management strategies and no interventions (that we know of) have addressed this issue directly in rural settings. Although water with residual chlorine is likely to be compromised when served in a contaminated glass (due to the short contact time involved), its disinfection effect could reduce the risk of contamination in subsequent servings. Washing glasses with soap, rinsing them with disinfected water, improving the hygiene of areas where drinking glasses are kept, and hand washing are all likely to reduce contamination of the drinking vessel. However, additional technical and social research is needed to identify key contamination mechanisms and determine strategies that result in effective and consistent elimination of drinking water contamination when using a glass. This finding also underscores the importance of collecting samples as close as possible to point of ingestion when evaluating water programs that seek to improve drinking water quality.

Although the model (by design) does not allow us to derive casual inferences, the results were useful for improving the Mesita Azul program guidelines and generating broader hypotheses of the contamination mechanisms and pathways of household water management. This model can be adapted for other HWTS technologies. We recommend the application of process-based models in household water management studies and their incorporation into trials that seek to evaluate the impact of HWTS programs.

6. CONCLUSIONS

- The Mesita Azul program allowed complying households (those that used UV system and narrow-necked storage container) to significantly reduce the presence of *E. coli* in drinking water.
- *E. coli* concentrations were similar in water collected via drinking cups from garrafones filled with UV-treated water and from purchased garrafones. Thus, the UV system enabled isolated rural households to access equivalent drinking water quality to that purchased from treatment and bottling facilities located in urban areas.
- Storing treated water in containers that are not covered, have a wide opening, or require dipping a cup to extract water limited the efficacy of UV disinfection in reducing drinking water contamination.
- A small number of samples contained low levels of contamination immediately after treatment with UV system. Most contamination of UV treated water occurred during storage. The use of a drinking glass introduced further contamination, a finding that affects most drinking water management strategies.
- The post-contamination process model identified several factors that were associated with the presence of *E. coli*. Inadequate household infrastructure conditions were positively associated with contamination of treated water, whereas additional storage time and number of extractions were associated with a decrease in the presence of *E. coli* in UV treated water. Experienced operators were associated with lower E. coli levels.
- Further effort is needed to develop effective strategies to reduce contamination during storage and at the drinking glass.

Chapter 5. Greenhouse Gas Emissions of Household Water Treatment in Mexico[8]

1. INTRODUCTION

Most households in Mexico consider that water from municipal piped systems is unsafe to drink (Cisneros 2008). Reasons behind this perception include: inconsistent chlorination; aging infrastructure; the need to store water at the home due to intermittent service; an increase in salinity or hardness due to overexploitation of aquifers; and constant marketing campaigns that frame bottled water as being healthier than piped water (Erickson 2012). This perception has contributed to a major shift in how households source and manage water for drinking purposes, resulting in Mexico being the largest consumer of bottled water worldwide (Malkin 2012; Pacific Institute 2010).

A recent study estimated that 80% of urban households drink bottled water, typically in reusable 20 L containers (*garrafones*), 10% drink water from municipal systems, and 10% drink water filtered or disinfected at home (Banco Interamericano de Desarollo 2010). The growing reliance on bottled water has significantly increased the percentage of household expenditures that are invested in securing safe water, particularly among low-income sectors (Erickson 2012). In addition to its high costs, producing and distributing bottled water is energy intensive (Gleick and Cooley 2009) and has been associated with negative environmental impacts (Gleick 2010).

In a context in which municipal piped systems are unlikely to guarantee the consistent provision of safe water in the near term, certain household water treatment (HWT) technologies can be a more cost-effective and environmentally friendly alternatives than *garrafon*-bottled water. Despite its growing momentum in other regions of the world (Clasen et al. 2011; Mintz et al. 2001; Sobsey et al. 2008), the HWT approach has remained in the sidelines of Mexican government entities (Lang et al. 2006). One exception has been the Mexican Institute for Worker's Housing (INFONAVIT), which created the Hipoteca Verde program in 2010 to incentivize water and energy savings in the residential sector. As part of the program, Hipoteca Verde provides low interest rate loans to INFONAVIT beneficiaries (*derechohabientes*) for purchases of HWT technologies with the goal of offsetting the consumption of bottled water, and thus reducing energy use and greenhouse gas emissions (GHG) (INFONAVIT 2014).

With Mexico's housing infrastructure projected to double between 2005 and 2030, there exists significant opportunity to reduce future climate change impacts from residential energy use. In response to this, the Inter-American Development Bank (IDB) designed a sustainable housing program (Ecocasa) to supplement INFONAVIT's green housing initiatives. The Ecocasa program aims to provide loans based on the performance of eco-technologies and infrastructure changes that reduce residential GHG emissions. However, the lack of GHG emission metrics for

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[8] This chapter was submitted in a similar form as part of a report prepared for the Inter-American Development Bank (Reygadas et al. 2013).

HWT has prevented the Hipoteca Verde and Ecocasa programs from assessing the GHG reductions associated with HWT loans.

Through a research project funded by the IDB, we set out to investigate the GHG emissions associated with the use of HWT technologies in Mexico. Our main objectives were to: (1) carry out a literature review of existing studies assessing the GHG emissions of HWT technologies; (2) use secondary data to perform a life cycle assessment (LCA) capturing the embedded CO_2 equivalent emissions of HWT products; and (3) calculate a metric for the GHG emissions associated with the use of HWT technologies in Mexico (kg CO_2eq/m3).

In the following sections of this chapter, we present the current state of HWT in Mexico, the scope and boundary of our life cycle analysis, our method for estimating emissions associated with HWT systems, the existing data available and our assumptions, and our final results in kg CO_2eq/m^3.

2. HOUSEHOLD WATER TREATMENT IN MEXICO

Household water treatment (HWT) technologies can be used to address issues of physical, chemical, and biological contamination (Sobsey et al. 2008). Historically, boiling has been the most widely known HWT method (Rosa and Clasen 2010). However, the high energy requirements (with a theoretical minimum of 300 MJ/L) and fuel costs are two of the main factors that have limited its consistent and sustained practice (Sobsey 2002). HWT technologies that are more commonly used in residential Mexico include membrane filters that remove particles (larger than 1-20 μm, depending on filter type) and activated carbon filters that reduce the concentration of chlorine and some compounds that affect the taste of municipally delivered water. A smaller percentage of households also rely on softeners to reduce water hardness and reverse osmosis (RO) to decrease the salinity of water. Except for RO, these types of filtration technologies are not effective at removing pathogens, particularly viruses and bacteria (Maier et al. 2000). HWT technologies that eliminate or inactivate microorganisms started gaining more attention in the mid-1990s after the cholera pandemic that affected several countries in Latin America, but their adoption still remains low in Mexico (Lang et al. 2006; Mintz et al. 2001).

In 2000, Mexico enacted two standards to regulate the technologies and substances used to treat water at the household level (NOM-180-SSA1-1998 and NOM-181-SSA1-1998). These standards were replaced in 2009 with a new standard (NOM-244-SSA1-2008: *Equipos y sustancias germicidas para tratamiento doméstico de agua. Requisitos sanitarios.*), which states that in order to comply with the standard HWT technologies need to remove 99.99% of total coliforms (Secretaría de Salud 2009). It is important to note that the Mexican standards are quite relaxed in comparison with the World Health Organization HWT Guidelines, which include removal requirements for viruses and protozoa (WHO 2011a).

3. METHODS

3.1 SYSTEM SCOPE AND BOUNDARIES

The system in this study consisted of household water treatment technologies that were available to the public in Mexico and that complied with its national HWT standard (NOM-244-SSA1-2008). We grouped HWT products in the following categories according the type of treatment technology: filtration impregnated with colloidal silver, filtration impregnated with germicidal nano-particles, ultraviolet light, ozone, and reverse osmosis. We restricted our main analysis to HWT products that were approved by the Hipoteca Verde program and that were representative of each treatment category. However, to assess whether or not this was an adequate representation of the current baseline in Mexico, we carried out a separate analysis for alternative products that were not part of the Hipoteca Verde program. We present the list of products in Table 5.1.

For each selected product, we estimated direct and indirect emissions of materials, distribution, source water use, and electricity use to assess the greenhouse gas emissions per cubic meter of water processed by HWTs.

Table 5.1: Household Water Treatment Technologies analyzed for embedded and direct emissions.

Hipoteca Verde	**Type**	**Brand**
Purificador Sobre/Bajo Tarja	Filtration	Rotoplas
Vitapurex	Filtration	Materiales Sustentables
Home Water Purifier	UV	Instapura
Aqu-100G	Ozone	Aquwell
Alternative Products		
Mesita Azul	UV	Cántaro Azul
Flozone	Ozone	Ozotech
Purificador Osmosis Inversa	RO	Rotoplas

The following elements were not included in the life cycle assessment of HWT technologies:

- Disposal and waste of the HWT products. The disposal and waste may indeed have environmental impacts but the greenhouse gas emissions were considered to be minimal in comparison to a system's embedded and use-phase emissions.
- The embedded emissions of infrastructure or machinery in all stages of the household water treatment technology production were not included. Such infrastructure or machinery is used for several years or decades and is associated with the production and transportation of thousands of units, leading to minimal contributions to the total emissions of a HWT system.
- Activities of employees along the supply chain such as commuting were not included in the scope of this analysis.

3.2 LIFE CYCLE ASSESSMENT MODEL

To effectively address the environmental impacts of a system, the life cycle assessment (LCA) methodology is a flexible, wide-reaching approach to analyze and compare technologies, processes, and products across "life stages". The LCA framework identifies inputs, processes, and outputs specific to a study and develops a life cycle inventory (LCI) within designated boundaries. This inventory tracks the energy inputs across the life of a product, which can then be converted to greenhouse gas emissions by using emissions conversion factors (Hocking 1999; Lundin and Morrison 2002; Yves et al. 2004).

We calculated kg CO_2eq/m^3 for water processed by a HWT technology over its life cycle with an input-output model. We identified four major segments of a system's life cycle and model their emissions:

- System production,
- Transportation and distribution,
- Water treated over the lifetime of the system, and
- Electricity consumed during the lifetime of the system.

The resulting model was a life cycle assessment that computed specific energy requirements and emission outputs for the selected technologies. We produced baseline, low, and high emissions scenarios to reflect the possible ranges of several data inputs. These calculations were based on manufacturing data, emissions factors for materials, energy, and water, and assumptions about transportation and distribution.

4. EMISSIONS OF HOUSEHOLD WATER TREATMENT INPUTS

4.1 ELECTRICITY

Electricity is a key input in small and large-scale water treatment and distribution systems. Each cubic meter (m^3) treated or distributed has an energy expenditure (kWh/m^3) and a greenhouse gas effect expenditure (CO_2eq/m^3).

To estimate the GHG emissions associated to electricity consumption, we used the life cycle emissions metric that we developed for the Mexican power grid as part of our IDB research project (Reygadas et al. 2013). In this analysis, we calculated kg CO_2eq/kWh for Mexico using electricity generation data from the Mexican Electricity Commission (CFE 2013), emissions per kWh in Mexico (Santoyo-Castelazo et al. 2011), and global warming potential factors from the Intergovernmental Panel for Climate Change Second Assessment Report (Parry et al. 2007). For lack of national data, we used indirect and direct fuel conversion factors (kg CO_2eq per tonne or liter of fuel) from a 2012 United Kingdom calculator produced by the Department of Energy and Climate Change (DEFRA) and the Department for Environment, Food, and Rural Affairs (DECC) (AEA for DECC and Defra 2012).

Within the life cycle analysis, we took into account the extraction of fuels and natural resources, the processing and transportation of fuels, the manufacture and construction of infrastructure, the operation of power generation plants, and the construction, dismantling, and elimination of residues. We assumed both that every state in Mexico generated all of its electricity consumption and that the GHG emissions of the electric grid in the country were the weighted average emissions of all the states.

The result for the life cycle emissions of the Mexican power grid was 0.57 kg CO_2eq /kWh (Reygadas et al. 2013).

5. EMISSIONS PER LIFE CYCLE SEGMENT

5.1 MATERIALS EMISSIONS FACTORS

We estimated the embedded emissions of each system by multiplying the weight of its materials by greenhouse gas conversion factors for various materials found in the literature. We obtained material types and weights by consulting the product specifications available from manufacturers and distributers of HWT systems. For lack of granular data about these components, our approximation did not include the embedded emissions of labeling, wiring, and other small parts that may be a part of the equipment.

Many studies in the building, transportation, and materials industry have analyzed the life cycle environmental impact of a variety of materials. DEFRA and DECC provided emissions factors for materials over an effective “cradle-to-site” life cycle, including emissions from extraction, processing, manufacturing, and transportation of materials (AEA for DECC and Defra 2012). The Inventory of Carbon & Energy (ICE), produced by the University of Bath, maintained a compilation of thousands of studies that range in scope from “cradle-to-grave” to “cradle-to-gate” assessing the embedded carbon in various materials. The ICE version 1.6a contained over 1,700 studies (Hammond and Jones 2008). Due to data constraints across these studies, the ICE reported “cradle-to-gate” embedded energy and embedded carbon; as well as average embedded energy by fuel source for some materials. A study by the University of California, Davis Institute of Transportation (IT) looked at embedded carbon dioxide equivalents and reported both the embedded energy and the ratio of different fuel sources that make up that energy cost (Delucchi 2003).

In both the Bath ICE and Davis IT studies, we used embedded energy values to calculate carbon dioxide equivalents based on fuel properties and life cycle emissions conversion factors. We added a conservative transportation (longer distance) emissions factor to those emissions factors that did not include transportation between the product production site and store. Finally, plastics material emissions were available from an extensive study that included three databases of plastic resin production emissions (Franklin Associates 2009a). We have included a comparison of conversion factors between the Davis IT, Bath ICE, Franklin, and DEFRA and DECC values in Table 5.2.

Table 5.2: Household water treatment: materials conversion factors.

Material	ICE kgCO_2/kg material	ICE kgCO_2eq/kg material	Franklin (2010)[1] kgCO_2eq/kg material	Delucchi (2008) kgCO_2eq/kg material	Defra & DECC (2012)-UK kgCO2eq/kg material
Polypropylene	3.90	--	1.95	--	3.25
General Plastic	2.53	--	2.7	--	3.18
Ceramics[2]	0.65	1.23	--	--	--
General Steel[2]	1.77	--	--	1.89	2.71
Stainless Steel	6.30	--	--	3.9	--
Small Electrical Items	--	--	--	--	1.76

[1] Franklin (2010) numbers here report an average of three databases reported in the source.

[2] General Steel and Ceramics numbers did not originally include transportation; using a conservative estimate of 3,000km of transport, we added the resultant 0.15 kgCO_2eq/garrafon to these values. Eventually these values get divided over the lifetime of water treated by the HWT. Additionally, general steel did not have an energy breakdown, preventing a calculation for carbon dioxide equivalence.

[3] Highlighted values represent conversion factors selected for analysis.

We selected values from these sources by prioritizing those values that were available (directly or through conversion) in carbon dioxide equivalence, came from a life cycle analysis with transparent methods, and were as relevant to Mexico as possible. In those cases where none of our criteria were met, we chose the highest value for a conservative estimate of "cradle-to-site" material emissions (Table 5.3). We estimated activated carbon as plastic because of lack of emissions data for this material and the high proportion of plastic in this type of filters.

Table 5.3: Embedded Emissions of materials used in household water treatment technologies.

Material	kgCO_2eq/kg material	Source
Polypropylene	3.25	Defra/DECC (2012)
General Plastic	3.18	Defra/DECC (2012)
Ceramics[1]	1.23	ICE (2008)
General Steel	2.71	Defra/DECC (2012)
Stainless Steel[1]	6.30	ICE (2008)
Small Electrical Items	1.76	Defra/DECC (2012)

[1] Stainlessl steel and ceramics numbers did not originally include transportation; using a conservative estimate of 3,000km of transport, we added the resultant 0.15 kgCO_2eq/garrafon to these values. Eventually these values get divided over the lifetime of water treated by the HWT. Additionally, stainless steel did not have an energy breakdown, preventing a calculation for carbon dioxide equivalence.

5.2 TRANSPORTATION AND DISTRIBUTION

There was no data (to our knowledge) on the distribution and transportation of household water treatment technologies to the home. Using the known weight of HWT technologies with assumptions about transportation and delivery, we approximated the emissions associated with transporting the HWT product from the plant to the store and from the store to the home. Without estimates of fuel use or distribution patterns we approximated a plant-to-store baseline distance of 1,500 km. We used an emissions factor for kg CO_2eq/tonne-km based on energy data from the National Energy Technology Laboratory and emissions factors from DEFRA and DECC (AEA for DECC and Defra 2012; National Energy Technology Laboratory (NETL) 2008). Our calculated value of 0.53 kg CO_2eq/tonne-km for standard trucks corroborates well with a study that reports average emissions of 0.50 CO_2eq/tonne-km for single unit and combination trucks carrying cargo in the U.S. (Schipper et al. 2010). These transportation values were added to those materials for which their emissions factors did not include a cradle-to-site analysis (ceramics and stainless steel). We did a sensitivity analysis and found that increasing the distance up to 10,000 km did not result in significant changes in the total LCA emissions of the HWT products.

For transportation of HWT products from stores to households, we approximated a baseline 6 km round trip based on interviews and maps of several cities in Mexico overlaid with stores where Hipoteca Verde approved products are sold. We used a vehicle efficiency of 11.8 km/L (Global Fuel Economy Initiative and UNEP 2010).

We assigned the consumer trip to the store an allocation factor of 75% to reflect the assumption that the first time purchase of a HWT system requires information gathering and is likely a planned purchase. In the case of transportation for replacement cartridges in filtration systems, we assigned a 50% allocation factor. This lower allocation reflects the assumption that consumers know exactly what they are purchasing (a specific filter) and will likely include other trips and errands into their biannual purchase of replacement filters. We also explored low and high emissions scenarios by manipulating transportation distance, vehicle efficiency, and allocation factors (Global Fuel Economy Initiative and UNEP 2010; Schipper et al. 2010).

5.3 WATER FROM MUNICIPAL PIPED SYSTEMS

Water distribution systems are increasingly being analyzed with the life cycle analysis (LCA) approach, which includes engineering optimization, economic, environmental, and social dimensions of design (Yves et al. 2004). Several studies in the literature have developed comprehensive life cycle costs for water distribution systems (Hocking 1999; Lundin and Morrison 2002; Skipworth et al. 2002). However, we found no LCA studies of GHG emissions of residential water use in Mexico.

In our IDB research project, we combined our result for the life cycle emissions of the Mexican power grid (0.57 kg CO_2eq /kWh) with water consumption data from the Mexican Water Commission (Comisión Nacional de Agua 2011) to develop the first metric of GHG emissions embedded in municipal water distribution systems in Mexico.

Even if water distribution systems involve various phases, we only included capture, treatment, conveyance, and distribution of water because these operations are the most affected by marginal changes in the residential household water demand (GIZ and CONUEE 2011).

The result for the life cycle emissions municipal piped water systems was 0.26 kg CO_2eq/m^3 (Reygadas et al. 2013).

5.4 WATER TREATMENT EMISSIONS (ELECTRICITY USE)

The household water treatment technologies assessed here required electricity as their primary energy input. A literature review of each treatment type considered (filtration with germicidal properties, ozone, UV, and reverse osmosis) contextualized the data we used to calculate direct emissions from the Hipoteca Verde and alternative products. Given the different treatment scales in the literature review, we compiled the data to produce a range of energy use per volume of water treated represented by most studies. We also used energy consumption and flow rate data from the manufacturers of HWT products to compute the energy use per volume of water treated. In both cases, we converted kWh/m^3 to kg CO_2eq/m^3 using the baseline emissions factor (0.57 kg CO_2eq /kWh) of the Mexican power grid (Reygadas et al. 2013). We calculated low and high literature values using the first and third quartile values for all of the literature data collected (Table 5.4).

5.4.1 FILTRATION

Filtration devices act as physical barriers to particles and objects in incoming source water. In household drinking water technologies, filtration is usually gravity fed and does not require electricity; therefore no direct use emissions result from using filtration devices.

5.4.2 OZONE

Ozone treatment is an oxidative water process that disinfects a wide spectrum of bacteria, viruses, and protozoa. At the household scale, ozone must be produced on-site and passed as a gas through the source water to properly disinfect it. As such, electricity is required to generate and operate the system. The U.S. Environmental Protection Agency's (EPA) water treatment standards require a contact time of ozone with the source water of four to five minutes at a concentration of 1.6 to 2 g/m^3 for low turbidity water to achieve minimum Ct (concentration × time) values for effective removal of pathogens (US EPA 1999). We reviewed energy requirement data for ozonation from a variety of sources and converted this into kg CO_2eq/m^3 of water treated (Franklin Associates 2009b; Gleick and Cooley 2009; Gottschalk et al. 2010; Masschelein 1992; Rakness 2005; SBW Consulting Inc. for PG&E 2006; US EPA 1999). We obtained a range from the bottom to top quartile of 0.0044 kg CO_2eq/m^3 to 0.0197 kg CO_2eq/m^3 with a median value of 0.0062 kg CO_2eq/m^3 for ozone treatment.

5.4.3 ULTRAVIOLET LIGHT

Ultraviolet (UV) light systems use short electromagnetic wavelengths (254nm) to inactivate waterborne pathogens by damaging their DNA and RNA. The UV light is produced inside a disinfection chamber by mercury lamps submerged or suspended above the water, depending on the system design. Based on a review of UV treatment systems using low-pressure lamps, which are relevant to the household water treatment scale, we found a range of wattages and flow rates that we converted to kg CO_2eq/m^3 of water (Cooley and Wilkinson 2012; Franklin Associates 2009b; Gleick and Cooley 2009; Masschelein 2002, 1992; SBW Consulting Inc. for PG&E 2006). We obtained a range from the bottom to top quartile of 0.0057 kg CO_2eq/m^3 to 0.012 kg CO_2eq/m^3 with a median value of 0.0086 kg CO_2eq/m^3 for UV treatment.

5.4.4 REVERSE OSMOSIS

Reverse Osmosis (RO) is a type of filtration in which source water passes through a membrane at high pressure, resulting in fresh water across the membrane and a rejected waste stream of ion and particle rich water (brine). The energy requirements of RO are significantly higher than those of filtration, ozone, and UV. Furthermore, the energy use and yield ratios of clean product water to untreated water depend on the concentration of total dissolved solids of the source water. Typically, increasing ion concentrations in the source water increases the energy use of the system and requires a higher ratio of source water to product water. We present values from the literature (converted to kg CO_2eq/m^3) by ion concentration (in ppm) in the table below alongside the other water treatment processes (see Table 5.4). We reproduced the values found in Gleick (2010) because the ion concentrations represented are relevant to household water treatment and the energy requirements reported were within the range of other values reported in the literature (Cooley and Wilkinson 2012; Franklin Associates 2009b; Gleick and Cooley 2009; Mayer and DeOreo 1999).

Table 5.4: Water treatment processes relevant to HWT technologies.

(Cooley and Wilkinson 2012; Franklin Associates 2009b; Gleick and Cooley 2009; Gottschalk et al. 2010; Masschelein 2002, 1992; Rakness 2005; SBW Consulting Inc. for PG&E 2006; US EPA 1999). Medians are calculated from multiple sources except in the case of reverse osmosis, where we report a range of values from Gleick (2010).

Water Treatment Process	Range	Direct Emissions (kg CO_2eq/m^3)	Sources
Ozone	Low	0.002	Gottschalk (2010); AWWA (2005); Masschelein (1992); Gleick (2010); Franklin (2010); EPA (1999); PG&E (2006)
	Median	0.006	
	High	0.061	
Ultraviolet Light	Low	0.004	Masschelein (1992, 2002); Cooley (2012); Franklin (2009); Gleick (2009); PG&E (2006)
	Median	0.008	
	High	0.026	
Reverse Osmosis	500 ppm	0.337	Gleick (2010)
	1,000 ppm	0.403	
	2,000 ppm	0.541	

6. WATER CONSUMPTION AND PRODUCT LIFETIME

For baseline water consumption we estimated the treatment of 10 L (0.5 *garrafones*) per household per day based on a conservative estimate of two liters of water consumed per day in a five person household. Water that enters the home is from the municipal water treatment plant, and thus we used the emissions factor of 0.26 kg CO_2eq/m^3, estimated by Reygadas et al. (2013) and presented in the preceding section.

We estimated HWT product lifetimes based on the characteristics of its components and the manufacturer specifications. We used baseline lifetimes of eight and four years for high and medium strength materials respectively. For replacement filters we used the lifetimes specified by the manufacturers in total treated liters. By combining water consumption and source water emissions with product lifetimes, we produced an effective "usable life" in terms of water treated by each product. Embedded emissions of production and distribution were divided over this effective lifetime to calculate the embedded emissions per cubic meter of water treated by each HWT product. Daily water consumption, the source water emissions factor, and product lifetime values were varied to simulate low and high emissions scenarios to capture variability in the Mexican market and residential sector.

Varying product lifetime values also captured a feature of HWT system ownership that is otherwise not explored here: consumers may or may not use a product over its entire lifetime. If a consumer stops using a product before the lifetime assumptions presented here, then the metric will underestimate the emissions per cubic meter of water treated in that specific case. By exploring the range of lifetimes, we implicitly explored the possibility of consumer disuse of the product or noncompliance, which might reflect more realistic user behavior.

7. EMISSIONS FOR MODEL SCENARIOS

The following scenarios represent the different assumptions explored in our household water treatment model (Table 5.5).

Table 5.5: Household water treatment system model scenarios.

Household Water Treatment Scenarios

Factors	Input	Baseline	Low	High
Product	Lifetime: high durability products (years)	8	12	2
	Lifetime: medium durability products (years)	4	6	4
Electricity	Emissions of electricity (kg CO_2e/kWh)	0.57	0.29	0.72
Water	Emissions of piped water (kgCO2e/m3)	0.27	0.07	0.44
	Daily household consumption (garrafones)	0.5	1	0.25
	Distance between store and household (km)	6	3	10
Transportation	Attribution of trip: first time purchase	75%	25%	95%
	Attribution of trip: replacement purchases	50%	5%	75%
	Vehicle efficiency (km/l)	11.8	13.0	8.0

We found that Hipoteca Verde and alternative products that used filtration with germicidal agents, UV light, and ozone resulted in similar emissions (see Table 5.5), suggesting that using an average metric for HWT products was a robust assumption for systems that meet the Mexican HWT norm (NOM-244-SSA1-2008). Including reverse osmosis treatment in the metric average, however, did not adequately represent the HWT emissions baseline. Reverse osmosis was much more energy intensive than alternative treatment options. The RO product that we explored resulted in 5.4 times more emissions than the average Hipoteca Verde product. We did not include reverse osmosis in the final metric but rather suggest inclusion of a case-specific metric for reverse osmosis for locations that have high salinity water sources.

The baseline scenario for HWT technology emissions (presented in Table 5.6) resulted in an average life cycle emissions factor of 0.95 kg CO_2eq/m^3 for UV, ozone, and germicidal filtration devices offered by Hipoteca Verde. The low and high emissions scenarios resulted in a range from 0.30 kg CO_2eq/m^3 to 2.6 kg CO_2eq/m^3 (Table 5.7). The range from low to high represented a fourfold increase in emissions, reflecting the variability caused by: differences in electricity and water source emissions; transportation distances, efficiencies, and attribution factors; and usable product lifetimes.

Table 5.6: Baseline greenhouse gas emissions per cubic meter of water treated by various household water treatment technologies.

HWT System LCA Emissions

Hipoteca Verde	**kg CO_2eq/m^3**	**kg CO_2eq/garrafon**
Vitapurex	0.80	0.015
Purificador Sobre/Bajo Tarja	1.06	0.020
Aqu-100G	0.41	0.008
Home Water Purifier	1.52	0.029
Average	**0.95**	**0.018**
Alternative Products		
Mesita Azul	1.82	0.034
Flozone	1.17	0.022
Purificador Osmosis Inversa	4.99	0.094

Table 5.7: Household Water Treatment Emissions based on low, baseline, and high model scenarios reflecting differences in emissions, product lifetimes, and distribution.

Household Water Treatment Emissions

Scenario	**kg CO_2eq/m^3**	**kg CO_2eq/garrafon**
Low	0.30	0.01
Baseline	0.95	0.02
High	2.57	0.05

8. CONCLUSIONS

We carried out the first life cycle assessment of greenhouse gas (GHG) emissions of the production, distribution, and use of household water treatment (HWT) technologies. With this results, we constructed a GHG emissions metric per volume of water used for HWT products that form part of green mortgage programs in Mexico. The baseline scenario of our metric resulted in an average life cycle emissions factor of 0.95 kg CO_2eq/m^3 with low and high scenarios of 0.30 kg CO_2eq/m^3 and 2.6 kg CO_2eq/m^3 respectively.

We included an assessment of alternative technologies and found our baseline estimate to be an appropriate approximation for other HWT systems that were available in the Mexican market, except for the case of reverse osmosis, where emissions were approximately five times higher than the baseline. Thus we recommend using a separate metric for reverse osmosis with an emissions value of 4.99 kg CO_2eq/m^3.

Considering that the GHG emissions of the *garrafon*-bottled water sector in Mexico are 32 kg CO_2eq/m^3 (Reygadas et al. 2013), we found evidence that replacing *garrafon*-bottled water with HWT can offset GHG emission considerably. These results allow programs like Ecocasa and Hipoteca Verde to compute the GHG emission reductions associated to HWT product loans. Furthermore, by using metrics like the one we developed, INFONAVIT and other mortgage institutions can compare across different GHG emission reduction strategies and prioritize the most cost-effective ones.

It is important to note that, in order to offset the consumption of bottled water, HWT technologies need to address all physical, chemical, and biological contaminants present in source water. There could be cases where using a HWT product that just meets the lax Mexican standard would not ensure removal or inactivation of all contaminants (e.g. high salinity, arsenic, pesticides, and certain pathogens). In such cases, that particular HWT product or series of products should not be recommended to replace bottled water.

Conclusions

I begin my dissertation work with the development of the Mesita Azul, a household-based ultraviolet (UV) water disinfection system. Then I carry out a comprehensive evaluation of the adoption and use of the Mesita Azul and its field efficacy. As part of this evaluation, I collaborate with UC Berkeley researchers to design and implement a stepped wedge cluster-randomized trial in rural Mexico. Then, in another collaborative project to estimate greenhouse gas (GHG) emissions associated with residential water use in Mexico, I developed a life cycle assessment (LCA) of household water treatment (HWT) technologies in Mexico.

Throughout my dissertation I engage with the HWT field by complementing interdisciplinary research methods with grounded practice experience and combining summative (Does it work?) and formative (How and why?) questions. Using this approach, the main contributions of dissertation research to the HWT field are:

The development of the Mesita Azul, one of the first ultraviolet (UV) water disinfection systems designed specifically for rural households.

- Produced a user-friendly and aesthetically appealing HWT system through a series of human-centered design and field test iterations.
- Improved the germicidal performance of the UV chamber using tracer studies and biological assays. The additional UV fluence created a safety margin that allowed the system to remain effective throughout the lifetime of tis lamp and when used to treat higher absorbance waters.

The evaluation of the adoption and use of the Mesita Azul using a comprehensive compliance framework.

- Developed a safe drinking water compliance framework in which compliance is divided into adoption, access, knowledge, habit, and exclusive use components and further disaggregated by processes of procurement and consumption.
- Applied the compliance framework to evaluate the Mesita Azul program.
- Found that the Mesita Azul program significantly improved compliance, where compliance was defined as the habit of consuming safe water. Additionally, half the commercial *garrafon*-bottled water users pre-intervention switched to UV disinfection post-intervention.
- Developed two variants of the Mesita Azul program (Basic and Enhanced) to test if with additional user conveniences lead to significant improvements in compliance.
- Analyzed the compliance rates of each variant at each framework component, and calculated the full costs of the program – from community assessment to post-installation follow up visits – per household targeted, and per household adopting.
- Found that the Enhanced variant led to higher compliance while enhancements lasted; it was more cost-effective for Access and Habit formation. But compliance and cost-effectiveness degraded with time for our primary outcome, the habit of consuming safe water.

The evaluation of the field efficacy of the Mesita Azul using *E. coli* as a fecal contamination indicator in drinking water.

- Used an as-treated-analysis to isolate the impact of the system and carried out a series of controlled comparisons to reduce bias.
- Created a drinking water reliability framework to compare potential contamination impacts from different household water management practices.
- Found that Mesita Azul program allowed complying households (those that used UV system and narrow-necked storage container) to significantly reduce the presence of *E. coli* in drinking water and to obtain a more reliable access to safe water.
- Observed that *E. coli* concentrations were similar in water collected via drinking cups from *garrafones* filled with UV-treated water and from purchased *garrafon*-bottled water. Thus, the UV system enabled isolated rural households to access equivalent drinking water quality to that purchased from treatment and bottling facilities located in urban areas.
- Found that storing treated water in containers that are not covered, have a wide opening, or require dipping a cup to extract water limited the efficacy of UV disinfection in reducing drinking water contamination.
- Created a process-based logistic regression model to assess household risk factors for post-treatment contamination.
- Identified several factors that were associated with the presence of *E. coli*. Inadequate household infrastructure conditions were positively associated with contamination of treated water, whereas additional storage time and number of extractions were associated with a decrease in the presence of *E. coli* in UV treated water. Experienced operators were associated with lower *E. coli* levels. The use of a drinking glass introduced further contamination, a finding that affects most drinking water management strategies.

The LCA of GHG emissions of the production, distribution, and use of HWT technologies.

- Developed an LCA model and a series of scenarios to estimate the GHG emissions of HWT technologies.
- Calculated the emissions for representative products available in the Mexican market that met the national HWT standards, including the Mesita Azul.
- Found that LCA emissions for filtration, ozone, and UV products were similar and could be adequately represented by a single metric of GHG emissions per volume of water used. However, the emissions of reverse osmosis were five times higher than the average of the rest, and thus required its own individual metric.
- Generated evidence that GHG emissions of HWT to be 30 times lower than commercial *garrafon*-bottled water, justifying the expansion of current programs that finance HWT.

HWT has the potential to allow hundreds of millions of people to drink safe water, improving their health and quality of live. Three critical barriers that currently limit the potential of the HWT approach are low adoption rates, inconsistent use, and variability in drinking water quality. The individual contributions of my dissertation complement each other to better understand these barriers and inform the development of strategies to address them.

The compliance framework can allow researchers and practitioners to identify, for any given safe water approach, the practices at which compliance falters, and which practices can feasibly be strengthened to encourage sustained use. Conceptualizing "compliance" as a multi-part phenomenon can be both intellectually and practically useful for future HWT research and development. For example, the application of the compliance framework to the Mesita Azul was useful in identifying the challenges of achieving exclusive consumption of safe water, influenced in this case by the existence of multiple water access points in the household and a low priority for drinking safe water by a segment of the population. An analysis of these results identified potential strategies to address them outside of the existing HWT paradigm, such as expanding a narrow focus on drinking water to making all domestic water safe to drink or switching from a product-based to a service delivery model.

Considering the current unviability of monitoring water quality in real time, the reliability framework proved to be a useful tool to generate a more realistic representation of the variations in water quality that households are exposed to. The processed-based model was also useful in identifying areas that can be targeted by HWT programs to improve water quality outcomes. The incorporation of the reliability framework and process-based model in the evaluation of the Mesita Azul, showed that certain households experienced more water quality variability than others and singled out the principal factors increasing post-treatment contamination risks. This analysis informed strategies to reduce post-treatment contamination, such as providing additional training to targeted households. But it also identified the need of additional research to understand the causes of water quality variability and to develop effective strategies that reduce contamination risks during storage and at the drinking glass.

My dissertation fieldwork showed that the Mesita Azul can be more effective in establishing the habit of consuming treated water than the practice of purchasing *garrafon*-bottled water; and that this can be done without compromising the microbiological quality of water. The HWT GHG emission metric, provided further evidence of the advantages of HWT over *garrafon*-bottled water.

One aspect that limits the adoption of infrastructure-based HWT systems, such as the Mesita Azul, is the lack of financing mechanisms to spread the required capital investments in more affordable periodic payments. Traditional entities engaged in the water sector have been slow to create such financing products. In this context, the HWT GHG emission metric developed as part of my dissertation could be used to further attract the attention of climate change mitigation finance institutions, which have already taken the lead in developing financing mechanisms for HWT options. An analysis across the components of my dissertation served to identify future work opportunities, such as developing a mechanisms to finance the service delivery model of the Mesita Azul. The service model could be beneficial to increase compliance and could provide better feedback to financing institutions of the ongoing GHG emission reductions than product-based models.

The results of my dissertation research can inform the development of programs and policies to strengthen the HWT approach and contribute to addressing the water quality problems that affect millions of people in Mexico and other developing countries.

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