MATERIALS FOR MANUFACTURING LOW-TECH, LOW-COST CERAMIC WATER FILTERS AND THE BUSINESS MODELS FOR THEIR DISTRIBUTION IN CENTRAL AMERICA

by

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Abstract

Water is a critical resource to the human race, yet half the planet's population experiences water scarcity and 780 million people do not have access to clean water sources year round. For those with no other choice but to drink from contaminated water sources, they are at risk of contracting a broad range of diseases, most commonly diarrhoea, which the second largest killer of children under the age of five. Residents living in rural areas of developing countries are primarily at risk, lacking access to basic water infrastructure and medical services. To provide clean water to those in need requires culturally appropriate technology that is simple to construct and local made.

Ceramic Water Filter Pots (CWFPs) consist of porous clay that acts as a filter, which is coated with silver nanoparticles creating a system capable of removing 99.995% of bacterial pathogens from drinking water and built in any community in the world. Working with a nationally recognized NGO based in Nicaragua, Potters for Peace (PfP), this study aimed to determine the limiting factors of production of CWFP by examining the materials used in three factories in Nicaragua, and the business model used in Guatemala based EcoFiltro.

Field work was conducted in three factories in Nicaragua, and one factory in Guatemala. Visual observations of the production methods, testing protocols and business practices were documented visually and used to contrast the facilities production and businesses practices.

Clay samples were collected from the Maysuta (n=2) and Filtron (n=3) factories to be analyzed at the University of British Columbia. The Atterberg limits were determined on the samples and X-ray diffraction analysis was used to determine the mineral makeup of the five samples and the percentage and type of clay in each.

This study outlines the limits of clay composition, specifically montmorillonite, which can be used to manufacture ceramic water filters that make a viable ceramic filter, and contrasts the business models of two ceramic water manufacturers.

Preface

This dissertation is the original, unpublished work of the author, B. Nichols. All research design, data collection, and analyses are the independent work of the author.

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List of Acronyms

ASTM	American Society for Testing and Materials
BSWF	Bio-Sand Water Filter
CWFP	Ceramic Water Filter Pot
DNA	Di-ribonucleic acid
HWTS	Household Water Treatment and Storage
ICAITI	Central American Industrial Research Institute
IDW	Improved Drinking Water
JMP	Joint Monitoring Program
KJ	Kilo-joule
NGO	Non-Governmental Organization
PATH	Program for Appropriate Technology and Health
PfP	Potters for Peace
SNP	Silver Nano-Particles
SODIS	Solar Disinfection
UDHR	Universal Declaration of Human Rights
UDW	Drinking Water ladder
UNICEF	United Nations Children Fund
UVA	Ultra Violet light-A
UWD	Unimproved Drinking Water
WHO	World Health Organization
WSI	Water Stress Indicator
XRD	X-ray diffraction

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1 Introduction

1.1 Statement of the Problem

Water is a critical resource that is necessary to sustain life on earth. Near the end of 2016, the global population will have exceeded 7.4 billion people, growing at an annual rate of 10 million people per year (Tayman, Smith & Rayer, 2011). As the world's population increases, the quantity of water available to each person decreases; as a result, conflicts over water are rising, and climate change is altering weather patterns and shifting the planet's hydrological cycle (Gleick & Heberger, 2014). These shifts change the in- and outflow rates of fresh water to reservoirs such as glaciers, mountain snowpacks and aquifers, which billions of people have relied on for thousands of years (S. C. Rai, Gurung, Fund, & Raina, 2009).

Decreases in water within a given region can lead to the physical scarcity of water, which creates competition between communities as well as agricultural, economics activities and other businesses, all of whom are trying to meet their own needs (Mekonnen & Hoekstra, 2016). For at least one month of the year, 71% of the global population experiences water scarcity (Mekonnen & Hoekstra, 2016).

Currently, between 0.7 and 1.8 billion people do not have access to clean water, the majority of whom live in rural areas of developing countries (Onda, LoBuglio & Bartram, 2012). These areas are difficult to reach and tend to be far from infrastructure such as roads, water treatment plants, hospitals and other support services (UNICEF, 2009). Reaching fragmented populations in remote areas through conventional infrastructure is not cost effective (Gleick & Heberger, 2014). Therefore, providing water to the 1.8 billion people who are in need requires solutions that can be implemented by locals without relying on large-scale density-dependent projects.

Local technologies that can be utilised in the home to retrieve and store water are known as Household Water Treatment and Storage (HWTS) technologies. A wide variety of technologies are classified under HWTS, each of which has strengths and weaknesses. Ceramic water filter pots (CWFPs) are one of the leading technologies that are ideal for use by fragmented populations in locations where neither clean water sources nor adequate infrastructure are available. This is because of their simplicity to operate and manufacture, making them a culturally appropriate technology for rural residences of developing countries.

Ceramic water filter pots are clay pots that contain colloidal silver, a well-known antibacterial. The porous nature of the pot, combined with the antibacterial properties of the silver nanoparticles, reduce the incidence of disease in the field (J. M. Brown & Sobsey, 2007; Mwabi et al., 2011; Van der Laan et al., 2014) and are preferred over comparable water filtration technologies (J. Brown, Sobsey, & Proum, 2007; T. Clasen, Health, & Water, 2009; Hwang, 2003; Lantagne, 2001). Furthermore, CWFPs are a low-tech and low-cost water filtration solution that offers significant protection to the user, can be made almost entirely from locally procured materials and empowers users to look after themselves and their families (D. van Halem, van der Laan, Heijman, van Dijk & Amy, 2009).

The purpose of this study is to investigate the technologies, materials and processes used in Nicaraguan CWFP factories, and to explore how variations in the physical properties of the clay and its mineralogy affect the performance of CWFPs. This study also seeks to understand and contrast the marketing and business strategies implemented by different CWFP factories in Nicaragua (Filtron, Maysuta and Ceramica por la Paz) as well as one in Guatemala (EcoFiltro).

1.2 Thesis Objective and Significance

The main research question of this study is as follows:

> What are the physical properties and mineral composition of the clay used in operational ceramic water filter pot factories in Nicaragua, and how could these properties affect production and effectiveness of ceramic water filters?
>
> Secondly, this study will examine what are the current business models for CWFP in Nicaragua and Guatemala, and how are they gaining market share?

This investigation of the ceramic substrates used in CWFP production and the current CWFP factory business model used in Nicaragua and Guatemala are based on the following:

1. CWFP factories commonly do not have access to equipment, such as X-ray diffraction, to identify individual minerals in their clay, and instead rely on simple physical tests such as shrinkage and water retention to determine whether a body of clay is acceptable for use to produce CWFPs
2. Minerals such as montmorillonite are known to absorb more water. However, larger percentages of montmorillonite cause clays to swell during production and shrink in the firing process, thus placing stress on the CWFP and resulting in a poor product that is likely to break (Potters for Peace, 2011).
3. The mineralogy and size distribution of particles in clay used in CWFP production affects the shrinkage of the CWFP after firing, the porosity of the CWFP walls and the capacity of the CWFP to filter bacteria (Potters for Peace, 2011; Rayner, 2009).
4. CWFP plants are operated in a range of cultures and locations, making it difficult to obtain identical materials that will work with a standardized manufacturing process to create a filter that meets PfP criteria (Potters for Peace, 2011).
5. CWFP factories are currently operated as privately owned firms, community organized initiatives, and with regards to PfP, as a NGO support system that does not operate CWFP factories, rather they foster the startup, growth and success of other CWFP factories.
6. CWFP are primarily marketed to those who can not afford other water purifying technology except in some places like Nicaragua (EcoFiltro) and Cambodia (RDI) where CWFP have been designed as aspriational products that are culturally valued for more then their water filtration function.

The objectives of this research are:

- To analyse the physical properties of clay used in currently operating CWFP factories in Nicaragua
- To assess the mineral composition of existing filter factory clay substrates.
- To observe factories operating in Nicaragua and to contrast their production methodologies with one another as well as with Potters for Peace's best practices guidelines.
- To observe and describe the business models for each factory, outlining their strengths and weaknesses.

1.3 Thesis Outline

Chapter 2 consists of a literature review concerning the scarcity of water, the heterogeneous distribution of clean fresh water around the planet, the current state of the water crisis in the developing world and the complexities humanity faces in providing water to every person on earth. The end of Chapter 2 discusses the behaviour of clay particles and their function in pottery. Chapter 3 explains the research and testing methods used to gather data and conduct field observations during this study.

Chapter 4 contains the qualitative data collected from visiting the three factories in Nicaragua (Maysuta, Filtron and El Ceramica por la Paz), and one factory in Guatemala (EcoFiltro). Chapter 5 examines the manufacturing processes used by the CWFP plants visited in relation to the best practice principles set forth by Potters for Peace.

Chapter 6 assesses the marketing and business platforms of EcoFiltro and Potters for Peace – the two largest and most influential CWFP organisations in this study – and analyses the pros and cons of EcoFiltro's country-specific business model in comparison to Potters for Peace's global model.

Chapter 7 outlines the soil testing protocols used to examine the soil collected from the CWFP plants in Nicaragua, while Chapter 8 reviews the results and highlights the findings from each test.

Chapter 9 presents a discussion of the physical soil testing results from Chapter 7, the observational data from the factory visits and the business model comparison from Chapter 6.

Chapter 10 provides a summary of the conclusions based on the results in previous chapter. This final chapter also offers recommendations for future research regarding questions that were not answered in this study and would require further investigation in this field.

2 Literature Review

2.1 Water, A Basic Human Right

In 1948 The Universal Declaration of Human Rights (UDHR) was adopted by the United Nations General Assembly in Palais de Chaillot, Paris, consisting of 30 articles declaring the rights and protections granted to every human being. Article 25.1 states that:

'Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services, and the right to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his control' (United Nations General Assembly, 1948).

Currently, 1.8 billion people lack access to clean water sources, a problem which is the cause of preventable diseases that result in over 2.2 million deaths a year from diarrhoea-related illness (WHO & UNICEF, 2014). Although access to clean water is a human right, ratified in Resolution 65/292 on July 10, 2010 by the United Nations General Assembly, providing clean water is not free and it will become a larger problem as fresh water sources are stressed by growing populations and reservoirs such as glaciers and aquifers are diminished (Gleick & Heberger, 2014).

2.2 Global Water Supply and Cycles

Water is the most critical resource on the planet, and without it life could not exist. Seventy-one percent of our planet's surface is covered by water, of which only 2.53% is fresh water fit for human consumption (United States Geological Survey, 1984). Of the fraction of fresh water on Earth, 68.7% is frozen in glaciers, snow and frost, 30.1% is located underground and 1.2% is accessible on the surface, although only 0.26% is available for use (United States Geological Survey, 1984). Figure 2-1, taken from the U.S. Geological Survey, shows the known water on Earth and expresses what percentage can be found in each location. The total available fresh water to the human race is less than 0.0001% of all water on the planet.

Water is heterogeneously distributed and stored around the planet in different forms (Gleick & Christian-Smith, 2011). Water needs of communities – based on population, distance to water reserves, infrastructure and level of technology – shape the demand of water and the stress on the reservoir that a community is using (UNESCO, 2009). The human race depends on a small proportion of water reserves, which are shrinking due to over consumption, lower recharge rates and climatic shifts that alter the hydrological cycle (United States Geological Survey, 1984).

Renewable water sources are those with established and regular recharge sources (rain, snow, drainage etc.) that maintain a net positive recharge rate (Gleick & Christian-Smith, 2011). Withdrawals exceeding the recharge rate of a body of fresh water stress the reservoir capacity to maintain a positive recharge balance and thus reduce stored volume, which, in extreme cases, can completely exhaust the water supply (Gleick & Christian-Smith, 2011).

Non-renewable water sources are reservoirs that have no established and regular water recharge sources, or have water recharge rates that are extremely low (United States Geological Survey, 1984). Underground deposits are an example of non-renewable water reservoirs that can be exhausted. Renewable sources such as aquifers can become non-renewable deposits if withdrawal rates are so high that the water pressure drops and the void space where the water accumulates is compacted (Gleick & Palaniappan, 2010).

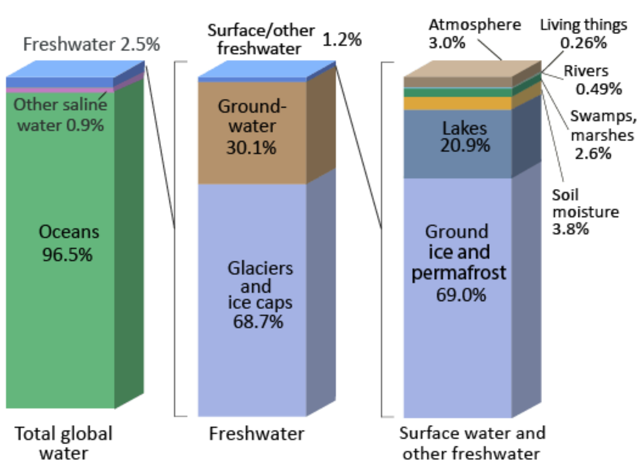

Figure 2-1: Global water accounting for sale and freshwater storages (United States Geological Survey, 1984).

The hydrological cycle shapes where water flows and is stored around the planet. Fresh water is stored in glaciers, icecaps and snowpack on land, from where it then melts and flows underground and into the ocean (United States Geological Survey, 1984). Changes in the hydrological cycle brought on by larger climatic changes can decrease reserves, thereby limiting the water available to flow through rivers, fill lakes and meet human needs (UNESCO, 2009).

The glaciers in Eastern Africa are an example of stored freshwater that have undergone accelerated melting, significantly reducing the fresh water available downstream which can be the largest single water source in the region (Barra & Chander, 2012).

Reduced freshwater flow over land has two effects: a decrease in the overall volume of water in rivers, lakes and wetlands, therefore increasing competition for available water; and a decrease in the quantity of water available to dilute anthropogenic waste and pollution that is washed away (Shevah, 2014). Water scarcity threatens not only those without drinking water, but also the industrial and agricultural operations which depend on water as a resource. Depleting water resources has the potential to escalate water competition, which can lead to conflict and may place those with the least access in serious risk.

Water conflicts between the years 1931 and 2012 are on the rise, as shown in Figure 2-2 (Gleick & Heberger, 2014). While the rise in water conflicts during this time frame is partly a result of the increased capacity to detect and report global conflicts, the trend can primarily be attributed to the increase in competition for dwindling freshwater resources (Gleick & Heberger, 2014).

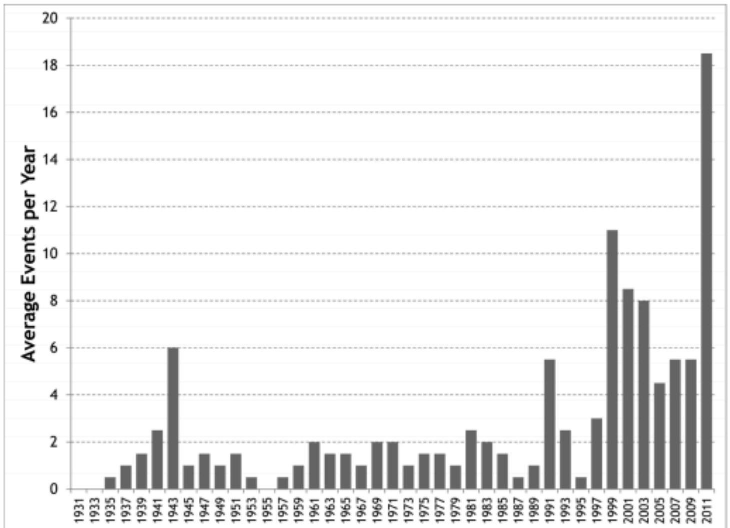

Figure 2-2: The number of reported water conflict events per year, 1931-2012 (averaged over two-year periods) (Gleick & Heberger, 2014).

The Indo-Gangetic Plains, a region consisting of Pakistan, India, Bangladesh and China, depend on the melt-waters from the Himalayan Glaciers, the second largest icecap in the world (Prasad, S. Yang, El-Askary & Kafatos, 2009). These glaciers, which one-sixth of the world's population depends on to meet their fresh water needs, are rapidly melting at a rate of 10-15m/year (S. C. Rai et al., 2009). Warmer regional temperatures have resulted in an early spring melt, which has changed the distribution of seasonal water flow (Kulkarni et al., 2007). This shift in the hydrological cycle is predicted to decrease summer flow rates and reduce the water available to downstream water systems relied upon for agriculture, industry and individual consumption (Jeelani, Feddema, Van Der Veen & Stearns, 2012).

Other regions of the world that depend on ice and snowpack for fresh water are also predicted to experience similar trends in the reduction of snow and ice deposition in the winter, followed by increased melt rates in the spring and decreased freshwater availability in the summer months (Schewe et al., 2014). Climatic shifts that reduce recharge capacity of fresh water reservoirs and exacerbate their erosion are likely to increase freshwater scarcity experienced on a global level.

2.3 Water Scarcity Factors

Global water stress is the combination of the total demand for water in relation to the current supply and recharge rates of existing reservoirs on a regional level (Smakhtin, Revenga & Döll, 2004). Figure 2-3 highlights water stress around the world calculated by the quantity of water available per capita in cubic metres in 2007 (Gleick & Heberger, 2014). Countries containing more than 2,500 m^3 per person are considered not to be in a stress state, and therefore have enough water to meet their needs as determined by the WHO (Gleick & Heberger, 2014; Ki-moon, 2015). Countries with less than 2,500 m^3 of water per person are considered to be in a state of vulnerability (Gleick & Heberger, 2014).

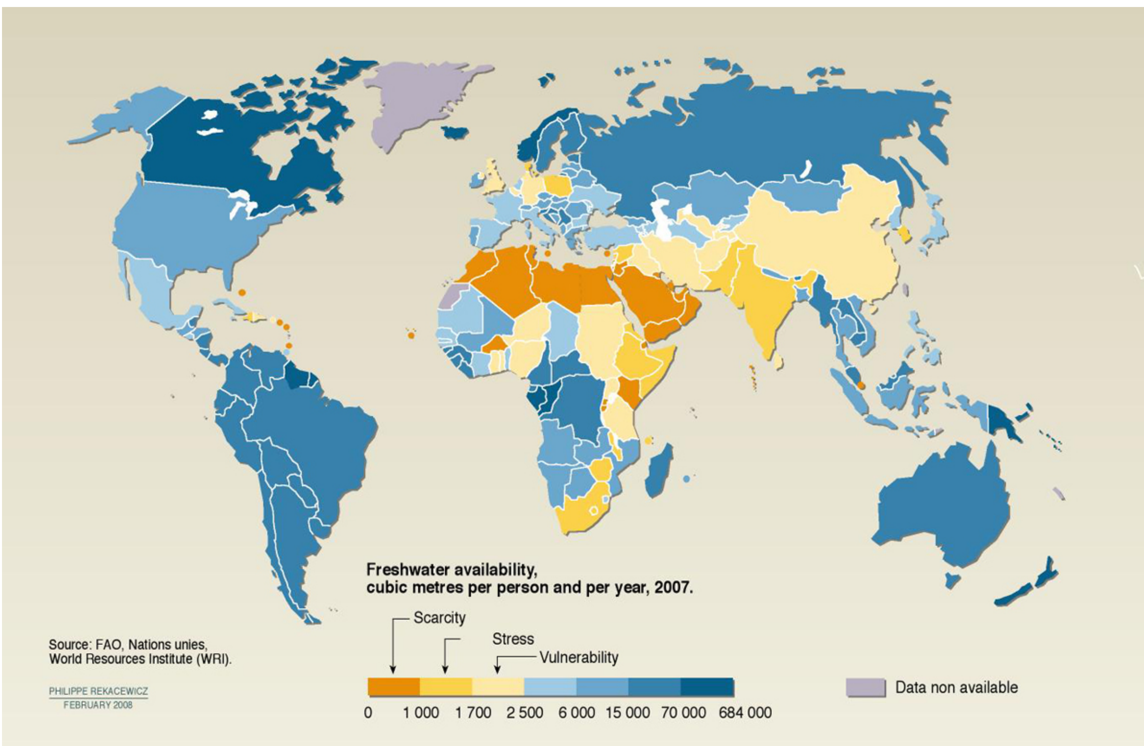

Figure 2-3: Global water stress (WHO & UNICEF, 2014).

Half of the world's population is currently at risk of not having its water needs met, and this figure is expected to rise. Three major factors contribute to the increase in future water scarcity: climate change, population growth and urbanisation.

2.3.1 Climate Change

Climate change resulting from the emission of gases such as carbon dioxide, methane, nitrous oxide, ozone, sulphur hexafluoride and others – which build up in the atmosphere and trap increasing amounts of solar radiation – has contributed to the rise in the earth's average temperature (Rosenzweig et al., 2008). Increases in atmospheric temperatures alter the complex cycles that shape the climate, weather and hydrological cycle on our planet (IPCC, 2008).

2.3.2 Population Growth

The current global population is approximately 7.2 billion, and this is expected to rise to 9.6 billion by 2050. Of this total, 2.3 billion people will reside in the developing world (Clay, 2011). Water scarcity is now a daily problem for 20% of the planet, and as demand grows – particularly in developing countries – such scarcity is predicted to increase (Gleick & Christian-Smith, 2011). In countries such as India, which contains 14% of the global population but less than 4% of the world's fresh water, population growth will see a further imbalance in the nation's fresh water per capita budget. This will be particularly difficult in urban areas where population densities are high and access to new sources of fresh water are limited (United Nations, 2014).

2.3.3 Urbanisation

For the first time in history, in the year 2007 more people lived in urban centres than in rural communities (United Nations, 2014). As urban populations continue to expand in the 21st century, stress on the freshwater reserves used by urban centres will grow disproportionately, potentially outpacing the resources recharge rate and exhausting the water supply (Nations, 2006).

The disproportionate population growth within urban environments is also accompanied by increased biological, chemical and consumption-based waste production, all of which contribute to water contamination if sufficient water treatment and protection is not provided (Gleick & Heberger, 2014).

Stress on a water resource can be described by five criteria: the physical properties and location of water; the access and distance to safe water; the capacity of a group of people to manage their water resources physically and in the marketplace; the use of water for residential, industrial and agricultural needs; and the health of the environment and ecosystem in which the water is stored (Sullivan et al., 2003).

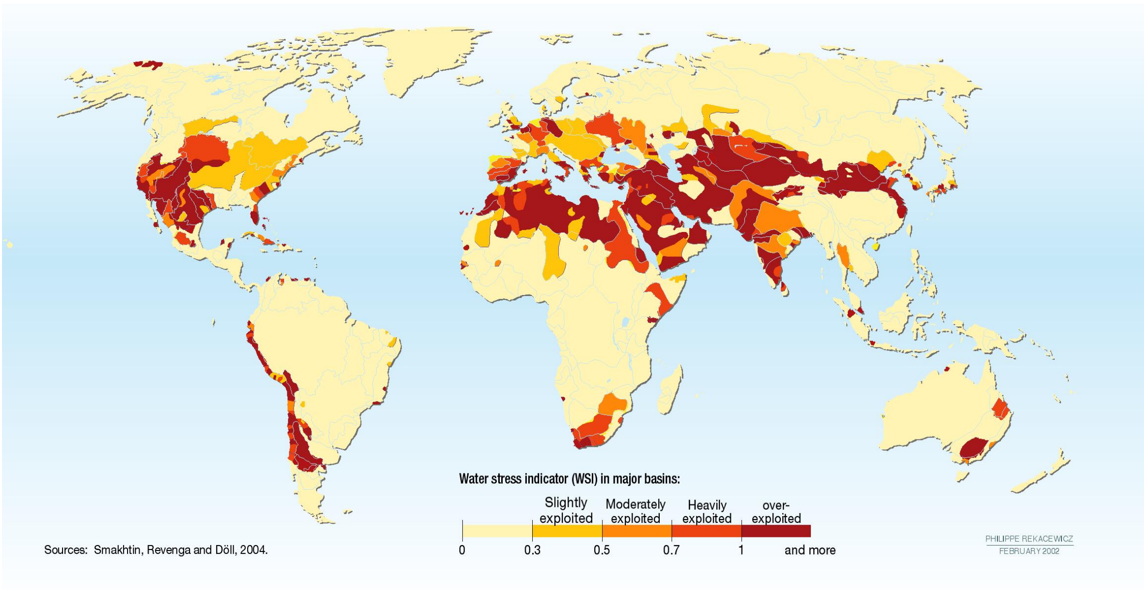

Figure 2-4: Global water stress (WHO & UNICEF, 2014).

The water stress indicator (WSI), shown in Figure 2-4, highlights regions of the world experiencing water stress ranging from zero (representing no water stress) or more than one (signifying the over-exploitation of a water resource). In 2006, the Human Development Report stated that an estimated 1.4 billion people live in regions where the water withdrawal rate is close to, or in excess of the recharge rate (Nations, 2006).

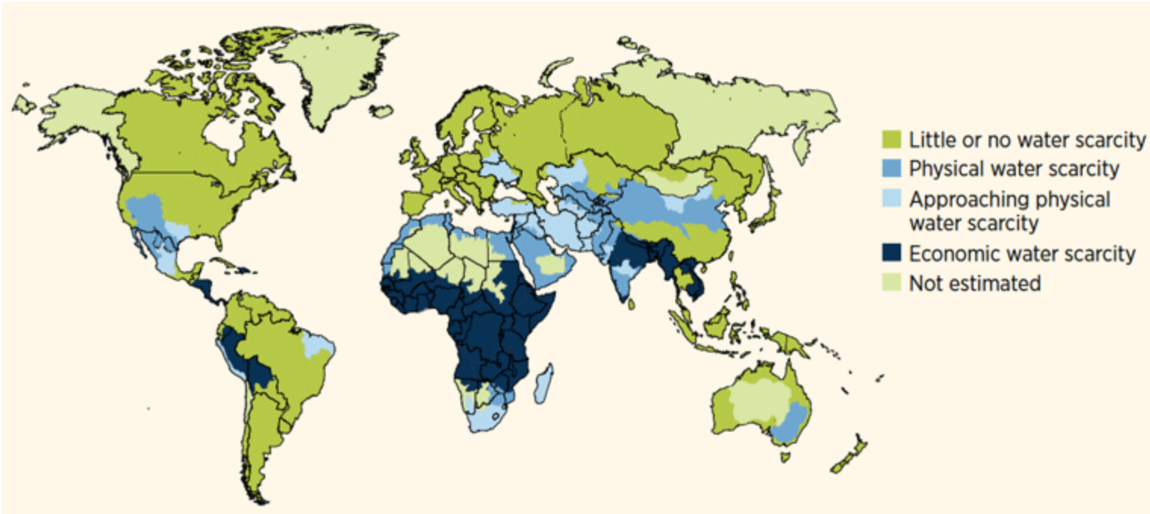

Figure 2-5: Global physical and economic water scarcity (World Water Assessment Programme, 2012).

Water scarcity also has an economic impact, as the cost of access to water can be prohibitive (Rijsberman, 2006). While water may be available in these regions, a host of other issues such as poverty, war, politics and private ownership may prevent individuals from accessing water resources. Figure 2-5 combines both the economic and physical scarcity of water, highlighting that first and third world regions are can experience water scarcity. In Bangladesh in the 1990s, 97% of the population did not have access to suitable drinking water, despite the region's abundant water resources. This situation was due to rising sea levels, inadequate drinking water protection and insufficient water management protocols (Abedin, Habiba & Shaw, 2014).

2.4 Protected Water Sources

Managing and protecting water sources is critical to meeting the needs of the expanding global population. The Joint Monitoring Programme (JMP) under the WHO tracks the quality and accessibility of drinking water projects around the world. To accurately compare water sources across regions and countries, the JMP developed a system referred to as the Drinking Water Ladder (DWL), shown in Figure 2-6. The DWL divides water sources into two categories: Unimproved Drinking Water (UDW), representing natural sources such as streams, lakes and rivers as well as man-made rudimentary containments like wells, tanks or bottled water; and Improved Drinking Water (IDW), referring to water that is protected by man-made infrastructure such as protected wells or springs, tube wells and piped water from treated sources (WHO & UNICEF, 2014). Water from UDW sources is at high risk of contamination from biological agents compared to water from IDW sources.

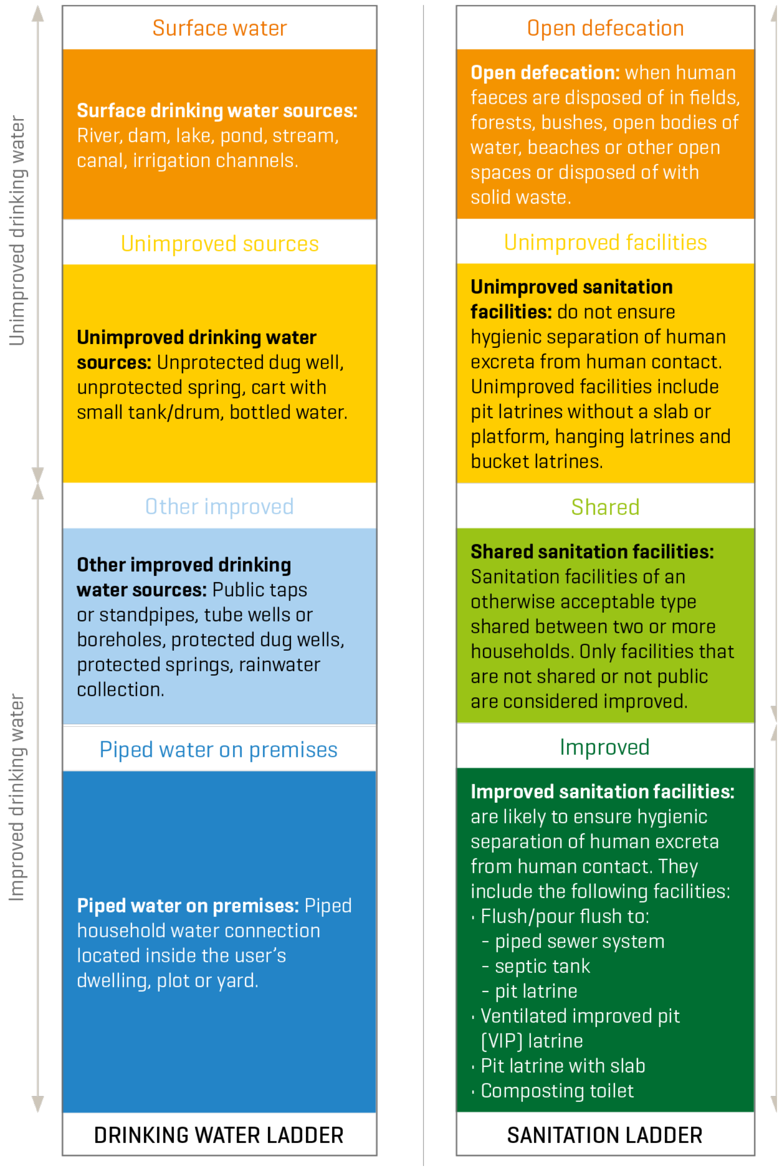

Figure 2-6: Drinking water and sanitation ladder (WHO & UNICEF, 2014).

Protecting water from biological or chemical contamination requires the management of both water and waste streams. The DWL also defines levels of sanitation to specify the state of biological waste infrastructure and improve the predictability of water contaminations resulting from poor biological waste management (WHO & UNICEF, 2014). To clarify the risks of drinking water from biological contaminates, the JMP created a supplemental Sanitation Ladder defining the level of infrastructure devoted to managing biological human waste as an additional protection for water sources.

2.4.1 Water-Borne Preventable Disease

The *Global Risks Report,* published in 2015, ranks water crises as the top devastating force against humanity and the eighth most likely disaster to affect mankind in the next 10 years (World Economic Forum, 2015). An estimated 748 million people lack direct and consistent access to clean drinking water, relying instead on a mixture of UDW and IDW sources when available (WHO & UNICEF, 2014). Preventable diseases that depend on water as a vector to move from host to host were responsible for an estimated that 3.4 million deaths in 2014 (WHO & UNICEF, 2014).

The World Health Organization estimates that 173 million people are solely dependent on UDW sources for their drinking water, 90% of whom live in rural areas of developing countries (WHO & UNICEF, 2014). The resulting burden of disease decreases individuals' capacity to work, shortens their lifespans, reduces their attendance to school/work and increases the stress on available healthcare systems, which in most developing rural areas are sparse or non-existent (Hutton & Haller, 2014).

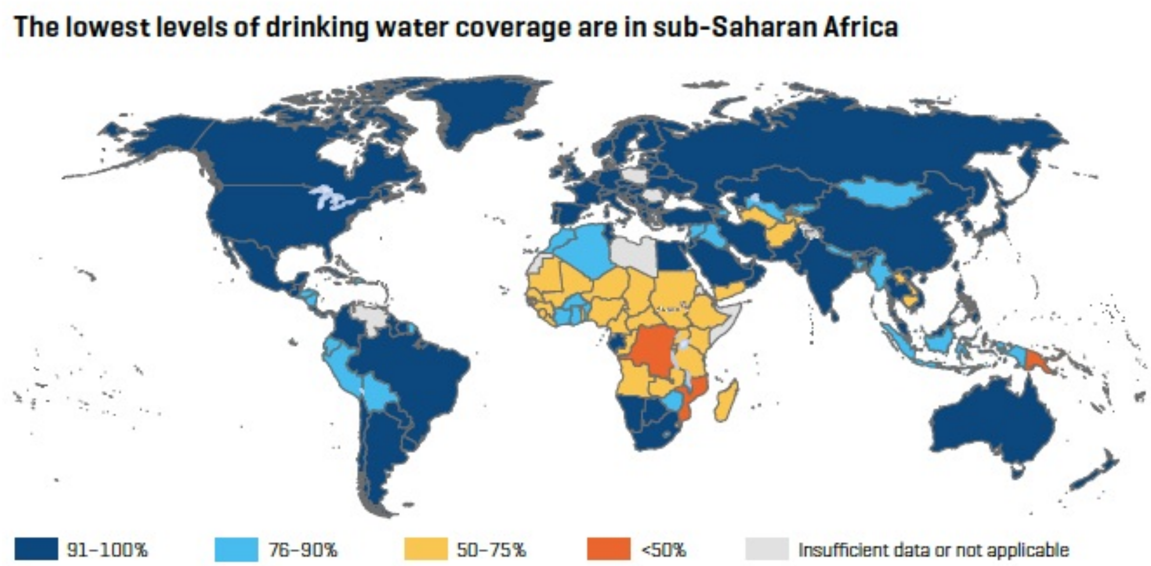

Figure 2-7: Proportion of the population using improved drinking water sources in 2012 (WHO & UNICEF, 2014).

The majority of those lacking access to drinking water live in Africa and Asia (WHO & UNICEF, 2014). In three countries – the Democratic Republic of the Congo, Mozambique and Papua New Guinea – less than 50% of the population has access to improved water sources (WHO & UNICEF, 2014). Figure 2-7 highlights the per capita access of a countries population to improved drinking water sources (WHO & UNICEF, 2014)

2.4.2 Children

Children are particularly vulnerable to disease due to their developing immune systems and low body mass. Furthermore, those under the age of five spend significant portions of their lives crawling on the ground, exposed to whatever natural hazards exist in their homes and communities (World Health Organization, 2005). During the 1980s, diarrhoea was the leading killer of children under the age of five, claiming the lives of 4-5 million children annually (Thapar & Sanderson, 2004). In 2012, diarrhoea was the second leading killer of children, killing 1.9 million a year, or roughly 5,000/day (Farthing et al., 2013). South-East Asia and Africa account for 78% of these deaths (Farthing et al., 2013).

On average, children under five years of age in developing countries will have three infections resulting in diarrhoea (Farthing et al., 2013). Prolonged cases of diarrhoea can result in severe dehydration and malnutrition, which weaken the immune system and make individuals more susceptible to other infections such as pneumonia. Children suffering from chronic diarrhoea are less capable of fighting off other secondary infections, which combined can lead to serious complications or death as a result of not having access to IDW sources.

2.5 Water as a Vector

Surface water is the most accessible source of water compared to other freshwater reservoirs, such as underground aquifers (UNESCO, 2009). Such accessible water is also at a higher risk of contamination from sewage, faecal material, animals, industrial runoff and other biological and chemical contaminates (Onda, Lobuglio & Bartram, 2012). It is therefore critical to have barriers in place in order to protect surface water from these contaminates, thus reducing the likelihood of diseases using water as a vector (J. Brown & Sobsey, 2010; Sagara, 2000; Tyeryar, Reed, Hackett, Gilmore & Abebe, 2005).

Contaminated water acts as a vector for diseases such as *Vibrio cholera, Giardia intestinalis, Cryptosporidium, Escherichia coli, Shigella* species and Salmonella, whose transmission is dependent upon faecal excretion from an infected host into or near water sources, which can then be re-ingested by other hosts to complete the pathogen’s life cycle. Protecting water sources from contamination is highly effective at preventing the spread of disease. Accordingly, improving sanitation infrastructure and hygiene habits is also a major step in reducing the prevalence of disease (UNESCO, 2009).

2.5.1 Sanitation

Between 1990 and 2012, 200 million people around the world gained access to improved sanitation facilities, which hygienically separate human excreta from human contact (WHO & UNICEF, 2014). In 2015 it was estimated that 2.4 billion people would be in need of improved sanitation facilities (WHO & UNICEF, 2014).

Over the past 22 years, 1.3 billion people have gained access to sanitation facilities, leaving 1 billion to defecate in their communities, potentially contaminating their water supplies (WHO & UNICEF, 2014). These individuals are a threat to themselves and their communities' health, as they propagate the spread of disease through faecal contamination of surface water sources (UNICEF, 2009). In the developing world, bacteria and parasites are most commonly the causative agents of disease; especially during the summer months (Farthing et al., 2013).

2.5.2 Diarrhoea

Diarrhoea is the increased fluid transfer to the lumen of the gastrointestinal system in order to flush the system of infections, toxins and internal irritants (Thapar & Sanderson, 2004). The WHO defines diarrhoea as the 'passage of loose or watery stool at least 3 times in 24 hours' (World Health Organization, 2005). This condition is the result of toxic proteins that are released by infectious agents (bacteria, parasites and viruses), which lead to an osmotic imbalance within the small intestine. Diarrhoea is clinically broken down into three groups:

Acute watery diarrhoea is the most common, has a sudden onset and lasts for several days, although it should not last for more than 14 days (World Health Organization, 2005). Acute diarrhoea is usually caused by an infection, drug, poison or hypersensitivity, and can be treated using oral rehydration salts and medication (Thapar & Sanderson, 2004).

Acute bloody diarrhoea, also referred to as dysentery, it is the result of an infection of the bowels that attacks the epithelial walls of the colon, which can cause the presence of blood in the stool (Thapar & Sanderson, 2004).

Persistent diarrhoea lasts for more than 14 days and is the result of persistent infections such as parasites, as well as co-infections such as HIV, pneumonia and urinary tract infections, which lower the immune system's capacity to fight infections. This type of diarrhoea is also caused by malnutrition or, most commonly, a congenital defect that affects gastrointestinal functions (Thapar & Sanderson, 2004).

It is estimated that roughly 4 billion cases of diarrhoea occur annually, 88% of which are the result of contaminated water (Hodges & Gill, 2010; WHO, 2007).

2.5.3 Causes of Diarrhoea

Diarrhoea is caused by several different species of bacteria, viruses, parasites and protozoa, as indicated in

Table 2.1. The majority of these pathogens are transported through the spread of human and/or animal faecal material, highlighted in brown.

To reduce the spread and perpetuation of diarrhoea, systems are required that: (1) separate faecal material from human contact, (2) prevent the contamination of water by biological contaminates and (3) store water in safe containers/systems that do not allow the proliferation of these pathogens.

Name of Organism	Major Disease	Major reservoirs and primary sources
Bacteria		
Salmonella typhi	Typhoid fever	Human faeces
Salmonella paratyphi	Paratyphoid fever	Human faeces
Other Salmonella	Salmonellosis	Human and animal faeces
Shigella spp.	Bacillary dysentery	Human faeces
Vibrio cholera	Cholera	Human faeces and freshwater zooplankton
Enteropathogenic E. coli	Gastroenteritis	Human faeces
Yersinia enterocolitica	Gastroenteritis	Human and animal faeces
Campylobacter jejuni	Gastroenteritis	Human and animal faeces
Legionella pneumophila and related bacteria	Acute respiratory illness (legionellosis)	Thermally enriched water
Leptospira spp.	Leptospirosis	Animal and human urine
Various mycobacteria	Pulmonary illness	Soil and water
Opportunistic bacteria	Variable	Natural waters
Enteric viruses		
Enteroviruses		
Polio viruses	Poliomyelities	Human faeces
Coxsackie viruses A	Aseptic meningitis	Human faeces
Coxsackie viruses B	Aseptic meningitis	Human faeces
Echo viruses	Aseptic meningitis	Human faeces
Other enteroviruses	Encephalities	Human faeces
Rotaviruses	Gastroenteritis	Human faeces
Adenoviruses	Upper respiratory and gastrointestinal illness	Human faeces
Hepatitis A virus	Infectious hepatitis	Human faeces
Hepatitis E virus	Infectious hepatitis; miscarriage and death	Human faeces
Norovirus	Gastroenteritis	Fomites and water
Protozoa		
Acanthamocba castellani	Amoebic meningoencephalitis	Human faeces
Balantidium coli	Balantidosis (dysentery)	Human and animal faeces
Cryptosporidium homonis, C. parvum faeces	Cryptosporidiosis (gastroenteritis)	Water, human and other mammal
Entamoeba histolytica	Amoebic dysentery	Human and animal faeces
Giardia lamblia	Giardiasis (gastroenteritis)	Water and animal faeces
Naegleria fowleri	Primary amoebic meningoencephalitis	Warm water
Helminths		
Ascaris lumbricoides	Ascariosis	Animal and human faeces

Table 2.1: List of bacteria, viruses and protozoa associated with diarrhea and intestinal infection (Farthing et al., 2013; Hodges & Gill, 2010).

2.6 Water Treatment and Storage

2.6.1 Household Water Treatment and Safe Storage Options

Household water treatment and safe storage (HWTS) protocols are critical to preventing diseases from living in water and being passed to humans. In areas where IDW sources are not available, people rely on UDW sources such as ditches, slow-flowing rivers, ponds or other water supplies that are easily contaminated by livestock, open defecation and industry effluent (Guerrant, Hughes, Lima & Crane, 2015). In order for these water sources to be safe for consumption, the water must be treated to remove or kill all biological contaminants.

There is a broad array of available water treatment options, ranging from boiling water to complex reverse osmosis filtration plants. For individuals living in extreme poverty, low-cost, low-tech water filtration operations are needed (WHO & UNICEF, 2014). Ideal water filtration solutions are simple to use and widely available, require minimum maintenance, use electricity and are highly effective at removing disease-causing pathogens.

A common view held in the literature is that HWTS are more effective when combined with water education on the spread of disease and hygiene practices (Heierli, 2008). When implemented effectively, HWTS have been shown to reduce diarrhoea by between 6% and 90% (Heierli, 2008).

In the developing world, a vast range of HWTS technologies are available that aim to address the needs of rural impoverished residences. These technologies fall into three categories: chemical disinfectants such as chlorine, flocculants and coagulants; thermal disinfection that uses heat to kill water-borne pathogens; and filtration, which removes biological pathogens directly from the water. The following sections explore these technologies as summarised in Table 2.2.

Water Purifying Technologies	Portable	Requires Energy	Community Preference	Daily Production volume (L)	Constructed from Local Materials	Removes Bacteria	Removes Viruses	Removes Turbidity	Revmoves Chemicals
Chemical Disinfectants									
Chlorination	Yes	No	Low	Varies	Yes	Yes	Yes	Yes	No
Coagulation & Flocculation	Yes	No	Low	Varies	Yes	Yes	Yes	Partially	Partially
Thermal Disinfectants									
Boiling Water	Yes	Yes (fuel/electricty)	Low	Varies	Yes	Yes	Yes	Yes	No
Solar Disinfection	Yes	Yes (Sun)	Low	Varies	Yes	Yes	Yes	Yes	No
Water Filtration									
Bio-Sand	No	No	Low	50-80	Yes	Yes	Partially	Partially	Possible
Ceramic Water	Yes	No	High	24-30	Yes	Yes	Partially	Poor	No

Table 2.2: Water purification technology comparisons (J. Brown & Sobsey, 2010; T. F. Clasen et al., 2015; Dawney, Cheng, Winkler, & Pearce, 2014; Duke, Nordin, & Mazumder, 2008; Hrudey, 2009; Sobsey, Stauber, Casanova, Brown, & Elliott, 2008).

2.6.2 Chemical Point-of-Use Disinfection

2.6.2.1 Chlorination

Chemical water treatment most commonly utilises chlorine, but other chemicals such as chlorine dioxide, ozone and iodine can also be used (Sobsey et al., 2008). The lipid cell walls and proteins of pathogens such as bacteria, protozoa and viruses are disrupted in the presence of these chemicals, leading to cell death (Thapar & Sanderson, 2004). To effectively treat water and ensure 99.95% of pathogens have been killed, a minimum concentration of chlorine must be used (Ashbolt, 2004). However, over chlorination can have toxic effects on end consumers of the treated water (Hrudey, 2009).

For chlorination to be implemented correctly, education and training are necessary to maximise the effectiveness of the treatment (Sobsey et al., 2008). Furthermore, chlorination supplies must be easily accessible in the community to ensure their continued use (Heierli, 2008).

To disinfect water, a chlorinating agent is added in a concentration of approximately 4mg/L, taking roughly one hour to disinfect a few litres of water (Hunter, 2009). If too much chlorine is used, it can add an unpleasant ‘chemical taste’ to the water. Minerals and organic material present in the water can also react with the disinfecting agent, decreasing the quantity of chlorinating agent available to disinfect the water and thus potentially reducing effectiveness (Hunter, 2009; Sobsey et al., 2008).

A broad range of variables can affect the success rate of chlorination, including time prior to consumption, presence of reactive material that may consume the chlorinating agent, the turbidity of the sample and concentration of the agent. Chlorination is typically not used as a stand-alone water treatment method, as it has a relative success rate of 29% (Arnal, Garcia-Fayos, Verdu & Lora, 2009).

2.6.2.2 Coagulation and Flocculation

Coagulation and flocculation achieving 45% success at removing pathogens from water; however, these methods require the use of a decanter, which increases the complexity of the process (Arnal et al., 2009). Added chemicals such as aluminium sulphate or iron (III) chloride react with suspended particles – both organic (bacteria, viruses, protozoa) and inorganic (clay, dirt, minerals) – causing these particles to precipitate (Sobsey et al., 2008). Like chemical disinfection, education and a steady supply of reactants are required to ensure proper water treatment. Unlike chemical disinfection, suspended solids that contribute to colour, turbidity and odour can be removed through gravity separation (Ahmed et al., 2010). This method can take several hours for particulates to settle, and without careful handling the solids can be stirred up again (Sobsey et al., 2008).

2.6.3 Thermal Disinfection

2.6.3.1 Boiling Water

Boiling water is an ancient and proven method to kill bacteria, viruses and protozoa, but is impractical based on the energy needed. Doing so requires a fuel source (coal, wood, gas, solar etc.) to heat water to a boil. The WHO advises that water be brought to a 'roaring boil' for a minimum of 8 minutes to ensure sufficient disinfection, or heated to the pasteurisation temperature of 60°C for 5 hours (Sobsey, 2002).

While this method is highly effective against nearly all pathogens other than endospores, it is estimated that one kilogram of wood – or approximately 320 KJ – is required to bring one litre of water to a boil (Sobsey, 2002). The expense of purchasing or collecting the energy needed to boil a day's supply of drinking water is a major disincentive for those practicing this technique (Sobsey, 2002). For those using combustibles (wood, coal, dung etc.) to heat water, who are most often women, factors such as air pollution and kitchen fires pose a serious health risk to them, their children and the surrounding community (Mishra, 2003; Rehfuess, 2006). The burning of wood fuels also contributes to deforestation (Sobsey, 2002).

Although boiling water is a simple technique, it is ineffective if the water is not heated to the specified temperature for a given period of time, and is also incapable of reducing the turbidity of the water.

2.6.3.2 Solar Disinfection (SODIS)

Solar disinfection of water harnesses the sun's energy to kill potential pathogens in transparent containers (usually polyethylene bottles) by destroying their DNA using UVA ultraviolet light (Hunter, 2009). To maximise the solar energy received, clean scratch-free bottles should be placed in areas where they receive maximum sunlight. Water with high turbidity cannot be used, as it will reduce the overall effectiveness of this method, which takes a minimum of 6 hours per bottle to achieve disinfection (Lawrie et al., 2015). Solar disinfection can be carried out in any location with sufficient exposure to the sun's rays, and where plastic bottles or other translucent containers can be found. The SODIS method neither removes particulates nor guarantees that the water will be safe to drink.

2.6.4 Filtration Types

2.6.4.1 Bio-Sand Water Filters (BSWF)

Bio-sand water filters (BSWFs) are point-of-use water filters that are an evolution from sand filters. Through the use of physical and biological processes, BSWFs can remove bacteria, viruses, heavy metals and protozoa as well as reduce odours, discoloration and bad tastes (White et al., 2013). Bio-sand water filters are usually constructed from concrete and filled with layers of sand and gravel, making them heavy (White et al., 2013). These filters are designed to use head-pressure to force water down through the filter layers and into a clean receptacle. The key feature is a bio-layer, which forms on the top of a pressed sand layer, followed by gravel for drainage. The bio-layer is home to established bacteria that feed on incoming bacteria and other biological components in the water that enters the filter.

Bio-sand water filters have varied success depending on upkeep, but have been found to reduce over 95% of biological contaminants in the field (White et al., 2013). The filters can be created from local materials, but are typically constructed on site since their weight makes them difficult to transport.

2.6.4.2 Ceramic Water Filter Pots (CWFPs)

Ceramic water filters are porous clay pots that water can flow through, while preventing solid material, bacteria and some viruses from passing through. These filters are typically made from a 50/50 mixture of clay and a combustible material (sawdust, coffee husk, rice husk etc.), which is fired in a kiln to create void spaces in the walls of the pot ranging from 5-30 micrometres in size. The dimensions of CWFP vary around the world, but typically most are designed to fit in a standard 20-gallon pail (75 liters), measuring 30.5 cm in diameter by 22.75 cm tall with a base of 22.25cm. CWFP are designed to fit in a pail or receptacle, as shown in Figure 2-8, which captures clean water that has passed through the filter.

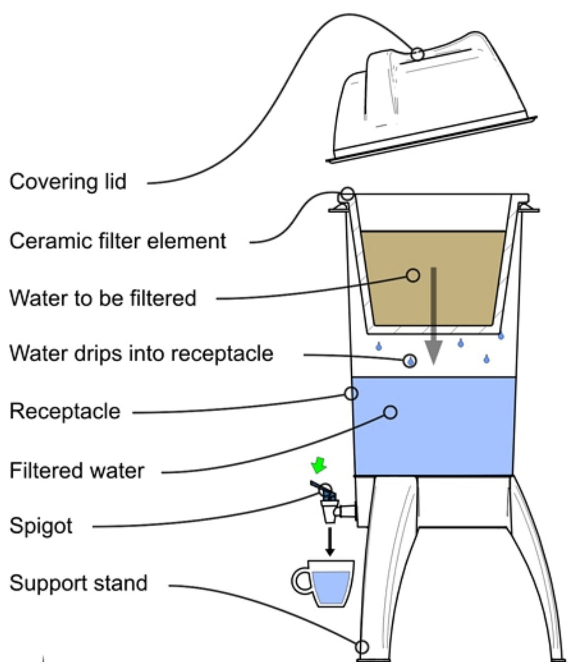

Figure 2-8: A CWFP unit cross-section diagram and flow of water from dirty to clean (Bolton, 2013).

Clean water is stored in the lower reservoir where it is isolated from contaminates prior to being drained from the bottom of the unit through the spigot at the bottom and consumed. A cross section and the dimensions of a CWFP filter collected from the Filtron filter plant in Nicaragua is shown in Figure 2-9.

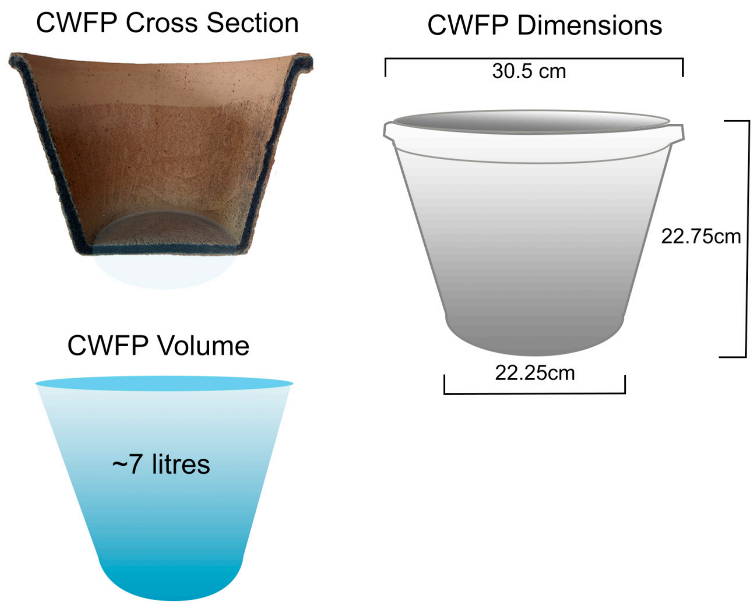

Figure 2-9: Filtron CWFP filter dimensions, volume and cross section (Rayner, 2009).

A CWFP can filter up to 2.5 litres per hour, providing up to 36 litres of water a day (Doris Van Halem, 2006). The ceramic filter element can filter up to 95% of bacteria and up to 60% of viruses under field conditions (Lantagne, 2001). Colloidal silver is painted on the inner and outer surfaces of the pots, where it binds to iron in the clay and acts as an antibacterial agent; this brings the CWFP's effective filtering capacity for bacteria to over 99.995% (Lantagne, 2001). Field studies have found that filtration capacities vary, but overall the filters have been shown to reduce the incidence of diarrhoea in Cambodia (J. M. Brown & Sobsey, 2007), South Africa (Mwabi et al., 2011), Nepal (Sagara, 2000), Nicaragua (Bielefeldt, Kowalski & Summers, 2009; Hwang, 2003), Mexico (Gutierrez-Jimenez, De Aquino-Lopez, Hernandez-Shilon, Schlie-Guzman & Vidal, 2014), Bolivia and Honduras (Lantagne, 2001).

Ceramic water filter pots are currently considered to be among the most promising household-scale water treatment options available to those living in developing countries (Lantagne, 2001; Roberts, 2004; Sobsey, 2002a).

Roberts 2004 study concluded that over 90% of the filter pots tested in a Cambodian village exceed the WHO low-risk criteria for drinking water, a criteria based on the bacteriological content of a given water supply and the potential risk it poses to a consumer (World Health Organization, 2006).

Both Sobsey (2008) and Roberts (2004) found that ceramic water filters were preferred over other water filtration technologies, primarily because of their ease of use. McAllister (2005) determined that people are more willing to trust locally made CWFPs because these contribute to the community's economic self-sufficiency and are technologically practical.

Ceramic water filter pots are an ideal solution for providing clean drinking water to the 783 million in need, because they are highly effective at reducing incidences of diarrhoea (Sobsey et al., 2008), can be locally manufactured and contribute positively to the local economy (Heierli, 2008). Additionally, CWFPs can be combined with other HWTS sanitation systems and hygiene practices to further increase their effectiveness. To contribute to the manufacturing and production understanding of CWFP, this study focuses on the properties of the ceramics used to manufacture CWFPs as well as the current marketing and distribution models employed by PfP and other organisations.

2.7 Colloidal Silver

Silver has been used since 4,000 BCE – long before the discovery of bacteria or antibiotics – to line water storage vessels and thus keep water fresh for months (Alexander, 2009). Hippocrates used silver on wounds and ulcers to reduce healing time, and people adopted the practice of adding silver coins to milk, beer and other liquids to prevent them from spoiling (Alexander, 2009).

Colloidal silver, which is a suspension of silver particles in a liquid, was first seen in the seventh century when physicians used silver nitrate to treat wounds and purify blood (Alexander, 2009). By the 19^{th} century, the use of silver in the medical field was commonplace, and silver's antibacterial properties were well established. Silver is an ideal antibacterial agent because it is highly toxic to bacteria, fungi and viruses, yet has a low toxicity in mammals, which is a critical property for fighting infections in human beings (Li et al., 2010).

2.7.1 Method of Action

There are two major types of colloidal silver compounds used as antibacterial agents: silver nitrate, which consists of silver ions (Ag+) suspended in water; and silver nanoparticles (SNPs), which are silver particles ranging between 1–100um that are suspended in a solution.

Silver ions can enter bacterial cells and inhibit enzymes, halting a host of vital functions ranging from DNA repair and replication to protein synthesis and ion pumps (Li et al., 2010). The exact ways in which SNPs inhibit bacterial growth and cause cell death are unclear (Rai, Yadav & Gade, 2009). Studies have shown that SNPs disrupt the permeability of a cellular membrane, then enter the cell and interfere with cellular proteins responsible for respiration (Li et al., 2010).

Applying colloidal silver to the inert surface of a CWFP creates a third antibacterial mechanism, catalysing a strong oxidation reaction (Heinig, 1993). This reaction depends on the volume of oxygen in the solution, along with the size of the SNPs and how they are dispersed (Heinig, 1993). The SNPs catalyse the oxidation of organic material in the water such as bacteria, viruses and other organics, which are killed or deactivated (Heinig, 1993). Oxidisable non-organic molecules also can be turned into downstream oxidisers, which increase the total antimicrobial effect of SNPs (Heinig, 1993).

2.8 Potters for Peace

Potters for Peace (PfP) began promoting the Ceramic Water Filter globally in 1998. These efforts were sparked by the water crises that followed Hurricane Mitch, which tore through Central America creating a state of emergency and disrupting the lives of millions (Potters for Peace, 2011). Potters for Peace ‘seeks to build an independent, non-profit, international network of potters concerned with peace and justice issues, while aiming to provide socially responsible assistance to pottery groups and individuals in their search for stability and improvement of ceramic production, and in the preservation of their cultural inheritance (PfP, 2001). The success of PfP depends on an alliance of potters from the developed North with their less technologically advanced partners in the South.

Specialising in education and training, the organisation has created and developed a model that focuses on establishing self-sufficient business owners who manage their own facilities. The filter, designed by Dr. Fernando Mazariegos of the Central American Industrial Research Institute (ICAITI) in Guatemala, was conceived as a simple solution that could be made anywhere from local materials, providing the poor with a way to treat their own water.

Since 1998, PfP has assisted with the start-up of more than 50 factories in over 35 countries around the world. In a 2009 survey of its partners, the 25 enterprises that responded reported an aggregate monthly production of 37,500 filters, or 450,000 filters per year (Rayner, 2009). If each filter serves a family of five, that means that in 2009, 2.25 million people gained access to clean water through CWFPs, which accounts for 3% of the people in need of clean water. PfP has helped lower the incidence of water-borne disease, diversify local economies and reduce the number of deaths caused by water borne diseases.

While this is certainly significant to those individuals affected, at the rate of 2.25 million people per year it would take roughly 330 years to meet the needs of the 748 million currently in need of access to clean water.

The estimated global production of 450,000 CWFPs per year does not take into account factories that did not participate in the 2009 study, nor does it account for other solutions such as SODIS, water chlorination, bio-sand filters and larger commercial systems that are being implemented each year.

2.9 Clay Minerals & Pottery

Pottery is an ancient technology developed by humans during the period from 20,000 to 12,000 BC in Eastern Asia (Craig et al., 2013). Little is known about how primitive humans developed and created ceramics, but the basic principle of wetting clay, then shaping and drying it into a shape to be heated to the point of vitrification is still present today (Craig et al., 2013).

Pottery is the art of combining clay with water to create a material that is plastic enough to be shaped, but stiff enough to lose that shape when unsupported. As water evaporates from the clay, the plasticity drops and the material becomes more stiff. To further strengthen the material, it is slowly heated to over 900°C; each ceramic has its own required temperature (Potters for Peace, 2011). This heating step turns the ceramic into glass in a process known as vitrification, which strengthens the material and makes it non-porous (Wowk, 2010).

2.9.1 Chemistry of Clay Minerals

Clay particles are the smallest classification of soil type, consisting of particles that are less than 0.002mm in diameter (Mitchel & Soga, 2005). Particles larger than 0.002mm are visible to the naked eye and can be quantified and measured using sieve analysis, as described by the American Society of the International Association for Testing and Materials (ASTM). Clays are evaluated by using a series of tests known as the Atterberg Limits to assess their plastic and liquid limits. The size of clay particles is inferred by the particle size analysis test as noted in the ASTM standard practice for the classification of soils (ASTM, 1993)

Aside from being small, clay particles have a net negative charge, become plastic when mixed with water and are highly resistant to weathering (Mitchel & Soga, 2005). There are four major groups of clay minerals (Sposito, 2008):

1. Alumino-silica
2. Carbonate and sulfate
3. Amorphous
4. Sesquioxide

The atomic structure of clay minerals dictates the physical structure of the mineral, its crystalline formation and how it interacts with other minerals, both physically and chemically. Alumino-silica clay minerals form two major crystalline structures: tetrahedral silicate sheets and octahedral hydroxide sheets (Mitchel & Soga, 2005). These sheets create three crystalline layer types that are described by the ratio of silica, aluminium or hydroxide sheets (Sposito, 2008).

Clay minerals that are comprised of one tetrahedral-silica sheet bonding to one octahedral-alumino sheet are classified as 1:1. A classification of 2:1 is the result of two tetrahedral sheets bonding with a single octahedral sheet, while 2:1:1 adds a hydroxide inner layer to the 2:1 configuration (Sposito, 2008). There are five groups of alumino-silicate clays (shown in Table 2.3), all of which derive their physical properties from their crystalline structure (Sposito, 2008)

Group	Layer Type	Chemical Formula of Layer Type
Kaolinite	1:1	$[Si_4]Al_4O_{10}(OH)_8.nH_2O$ (n= 0 or 4)
Illite	2:1	$M_x[Si_{6.8}Al_{1.2}]Al_3Fe.025Mg_{0.7}5O20(OH)_4$
Vermiculite	2:1	$M_x[Si_7Al]AlFe.05Mg0.5O_20(OH)_4$
Smectite	2:1	$M_x[Si_8]Al_{3.2}Fe_{0.2}Mg_{0.6}O_20(OH)_4$
Chlorite	2:1:1	$(Al(OH)_{2.55})4[Si_{6.8}Al0_{1.2}\}Al_{3.4}Mg_{0.6})20(OH)_4$

Table 2.3: Clay layer classifications and formulas (Sposito, 2008).

The strength of the bonds between each layer determines how the clays behave in the presence of water. Kaolinite, a common clay with a 1:1 crystal structure, forms strong bonds between the tetrahedral and octahedral layers, preventing substances like water from separating these bonds and thus making the volume of the crystals larger (Sposito, 2008).

Montmorillonite is from the smectite group and is comprised of seven layers – four oxygen, two silica and a single aluminium layer – creating a 2:1 silica-alumino crystal structure. Unlike kaolinite, the bonds between the layers are not as strong, causing them to separate in the presence of water and allow water between the layers (Sposito, 2008). In the presence of water, this causes the amount of montmorillonite to increase tenfold from its dry volume (Sposito, 2008).

2.9.2 Shape and Particle Size of Clay Minerals in Pottery

The shape and size of clay crystals can change the plastic, liquid and water absorption properties of a clay mixture, as well as those of the wares made from it. When mixed with water, clay particles and aggregates will form a colloid. The more water is added, the farther particles are from one another and the more plastic the clay becomes until reaching the liquid limit.

In the plastic state, void spaces between clay particles are occupied by fluid or gas. The size of these void spaces is determined by two factors: the shape of the particle (which is determined by the crystalline structure of the clay mineral), and the particle's size.

Clays that do not stack closely to one another, or are spherical, have larger void spaces compared to those that are complementary and fit closer together. Additionally, the particle size distribution of a clay can reduce or increase the void space within.

Mixtures containing only large particles will have large void spaces between each particle, which amounts to a larger volume to fill with water. The opposite is true of smaller particles, which can fit more closely together, thereby decreasing the total volume of the void space between particles.

As clay dries, the water between these spaces evaporates and is filed with air. If the combined spaces are too large, the drying clay will shrink and potentially crack.

2.9.3 Clay Properties of Ceramics

It is important that the clay used to make CWFPs does not shrink or expand excessively to the point that stress is created in the final product. Montmorillonite – which is highly plastic and seems ideal for forming CWFPs – can swell and shrink, resulting in cracking and breakage (Potters for Peace, 2011). Clay testing is an ongoing process to ensure that the clay collected, whether from a mine or surface location, displays the same physical and chemical properties. Changes in these properties will affect production, the material's response to processing and the final product.

The purpose of this study is to investigate the clay used at the operational CWFP factories in Nicaragua in order to assess the boundaries of clay properties that will produce CWFPs.

3 Research Methods

3.1 Introduction

This chapter introduces the mixed methods approach of this study, which applied both qualitative and quantitative research techniques to address the research objectives.

3.2 Choice of Methodology

This study utilised a mixed methods approach to pursue the research objectives described in section 1.2. This type of approach involves ‘integrating quantitative and qualitative data collection and analysis in a single study or a programme of enquiry’ (Creswell, Hesse-Biber, Leavy, Creswell & Eidlin, 2011), which can provide a broader understanding of research phenomena than either approach could do on its own (Clark & Creswell, 2007).

Qualitative research methods are ‘pragmatic, interpretive and grounded in the lived experiences of people’ (Marshall & Rossman, 2006). The purpose of qualitative methods is to understand natural phenomena through narrative data by using a holistic approach that is non-disruptive. The addition of quantitative data methods allows for the verification of data across both data sets, known as the triangulation methodology. This method maintains the separation of qualitative and quantitative data collection, such that the research team can approach a solution from two standpoints. Data are collected simultaneously for equal weighting in the study, after which both data sets are reported separately in order to bring their connecting points together.

The primary research methodologies used to gather data for this study are as follows:

- Literature review of documents, reports and web research
- Visual observations made of filter factories and clay mines during a 10-day field visit to Nicaragua, along with observations of water filtration technology in use during previous trips to Nicaragua and Guatemala
- Photos and videos taken to document and compare to other studies
- Clay samples collected for testing from factories and associated mines.

3.3 Researcher

Researchers have their own epistemological lenses that can shape their interpretations of events and people's actions (Marshall & Rossman, 2011). Prior to engaging in this research, the researcher had knowledge of biology, water quality and pathology, and views this project from a mining engineering and managerial perspective. The researcher's background and position were openly shared with all people who he came in contact with during this study.

3.4 Previous Research Experience

The researcher has spent 10 years organising and participating in field research studies on climate change, industrial ecology and watershed management, primarily in Northern Alberta. In 2013 the researcher lead a team of 10 researchers to Portovelo, Ecuador to investigate the use of mercury by artisanal miners in the region.

The observational challenges encountered by the researcher during this two-month project with regard to obtaining survey data and technical data influenced the data collection methods for this study. The researcher experienced several complications while conducting interviews in Spanish through translators during the Portovelo study.

The limited resources, field research time and access to potential Spanish-speaking interviewees prompted the researcher's decision to focus on the quantitative aspects of the study, and to limit the qualitative data collection to passive methods such as photos, video and observations.

3.5 Participants

No humans took part in this study as 'participants', meaning that no interviews or surveys were conducted to collect data on human beings. This study focused on the methodology of CWFP operations, the materials collected and used in the construction of CWFP, and how these processes vary between factories. Within the CWFP factory facilities, observational research techniques including photography, video and visual recording of the CWFP manufacturing process were employed.

3.6 Audience

The goal of this study is to communicate the research findings to academia, NGOs, the resource extraction industry and communities seeking technical advice on the physical properties of clay used to manufacture CWFPs. In the case of academia, this study lays the groundwork for future research into the use of ceramics at a community level. Community groups, companies and NGOs can use the information provided in this study to make changes to their current manufacturing procedures and identify clays that are incompatible for use in CWFPs.

3.7 Procedure

The author of this study was based in the Mining Engineering Department at the University of British Columbia in Vancouver, British Columbia, Canada. Due to the dispersed and remote locations of the CWFP factories around the world, the author approached the NGO Potters for Peace, based in Managua, Nicaragua, to coordinate a tour of the factories in that area. The factory visit to EcoFiltro in Guatemala occurred during a separate trip on April 1, 2016.

The remote location of the facilities, along with the language barrier and lack of communication between factories and PfP made it difficult to access factories and schedule tours. Each factory was first contacted by email to arrange a tour, but the researcher received no response. Instead, the researcher reached out to PfP to arrange tours of the CWFP factories in Nicaragua. Potters for Peace arranged three visits to facilities the organisation had previous knowledge of within Nicaragua. The established window to conduct research with PfP and visit the three factories when they would be open was from December 15th to 20th of 2014.

Each CWFP factory visit began with an introduction to the owner and the staff on site that day, a walking tour of the facility and demonstrations of each process, which were photographically documented and complemented with field notes.

Clay samples were collected from two factories – Filtron and Maysuta – and were analysed by the researcher in the Mining Engineering Coal Processing Laboratory at the University of British Columbia. The sample processing and analysis is discussed in Chapter 6.

The factory tour of EcoFiltro was primarily self-guided, with a brief meeting with the owner and a few of the employees in the factory. Observational data was gathered from the exhibits, observable processes and the material provided on behalf of EcoFiltro explaining their operations and programs in Guatemala.

To reduce error in interpretation from Spanish to English and to obtain unbiased data on production methods, the researcher chose to use observational research techniques in order to passively assess CWFP manufacturing methods.

3.8 Methodological Limitations

All research has its limitations (Patton, 1990), and understanding and discussing these the limiting factors is critical to defining the scope of the conclusions made in the study (Marshall & Rossman, 2006).

Due to the limited time frame available to conduct field research, not all facilities in the region could be documented, nor could more than a single day be spent at each facility. This study chose to investigate the three factories operating in Nicaragua, primarily because PfP are located Managua, Nicaragua, and could facilitate the field visit to the factories which were one day's drive apart from one another. The fourth factory visit of EcoFiltro, located near Antigua, Guatemala was made during an additional trip on a different project and due to time constraints; a longer field visit was not possible.

3.9 Ethical Considerations

No human beings participated in this study, nor was any personal information collected about the individuals working at the CWFP factories.

4 Field Observations

4.1 Filter Factory Visits in Nicaragua & Guatemala

From December 12th - 22nd of 2014, a research team travelled to Nicaragua to visit three factories where ceramic water filters were produced. Robert Pillars and Kaira Wagoner, both members of PfP, facilitated the tours of the CWFP facilities, provided introductions to factory management and translated from Spanish into English during factory tours when necessary. All factory visits were conducted from an observational perspective, observing the collection of clay and the manufacturing process. Data was compiled from the researcher's perspective on what occurred at each factory, equipment on site, inventory and the general state of the current operation.

4.2 Old Managua Plant - Ceramica por la Paz

Figure 4-1: The clay press of the old Managua CWFP factory.

4.2.1 Plant Description & Location

Ceramica por la Paz is located on the eastern edge of Managua in a rural commercial area, mostly surrounded by farms and old commercial operations. The grounds were overgrown and the single-storey wooden building was aged, with broken windows and other damage in need of repair. The facility was approximately 20m by 40m in size, although the equipment used to manufacture ceramic materials only occupied a 10-m by 15-m portion of the facility, leaving the majority of the factory empty. An old clay press, shown in Figure 4-1, is in the centre of the factory surrounded by disused equipment.

4.2.2 Current Operations

The current operation appeared to be only a fraction of what it once was. The equipment on site consisted of a filter press, hammer mill, compressor and wood-fired kilns, shown in Figure 4-2. On the day of the visit to the plant, the four workers were making clay kitchenware such as cups, plates and bowls.

Figure 4-2: The old Managua CWFP plant. Old destroyed kilns (left); clay filter press, compressor and operating kiln (middle); empty factory (right).

The clay used to manufacture the wares is gathered on site and from adjacent farms. Prior to use, the clay is processed in a hammer mill and filtered in a filter press. The use of a large filter press shown in Figure 4-1 is unnecessary for the production of CWFPs, and was used to produce clay with fine particle size distributions to create the smooth-walled ceramic wares the workers were making during the field visit.

The staff took greater care to make high-end products that were low in number, rather than aiming for volume. This could been seen in the facility's current inventory and the effort the workers put into each piece. Items such as these fetch much higher prices in local markets – especially when sold to tourists – or elsewhere abroad.

Figure 4-3: Old Managua filter plant. Clay cups being glazed (left), clay wares storage (middle) and two old kilns (right).

No ceramic water filters were made during the research team’s visit, and the necessary equipment for making the filters was not used. In the right image of Figure 4-3, two gas-fired kilns are shown. Neither kiln was in operational condition, nor were they hooked up to a functioning gas line. Outside, one small wood-fired kiln was in operation that could hold up to 50 ceramic filters. This kiln was being used to fire bowls and cups. The factory’s ceramic filter press was stored away behind some equipment inside the facility. The press consisted of a female and male mould welded into a hydraulic press. The press utilised a 20-tonne car jack to apply pressure to the moulds.

Due to condition of the equipment, as it had been stored out of reach behind several other pieces of equipment and was missing the jack, it was clear that this facility had not produced water filters anytime recently. No filters were located on site, nor were there any plastic pales or spigots available to accompany CWFP shipments.

The current operation could be capable of producing 25 filters per day, providing workers were able to operate the manual filter press continuously for 12 hours. The small wood-fired kiln is the limiting factor of production for this factory.

4.3 Filtron, La Maysuta

Figure 4-4: The Maysuta community CWFP factory and kiln.

4.3.1 Plant Description

The community-operated ceramic plant, Filtron, is located 25km south of the Honduran border in the community of La Maysuta (shown in Figure 4-4). La Maysuta is located south of the city Octal on the eastern side of the highway, down a narrow path only accessible by 4x4 vehicles. The CWFP factory, which doubles as a community centre, is a 4-m by 5-m building with a 3-m tin roof overhang. This was the newest and most modern building in the community.

Behind the building was a small shed, used to store materials and equipment, as well as two kilns: a small old kiln and the new larger kiln the community had built in the previous month. The large kiln, shown in the left image of Figure 4-6, was a considerable upgrade over the smaller kiln in the middle image.

The local community collected clay from a hillside 200m from the community centre shown in Figure 4-5. Hand tools were used to mine the clay, which was then carried down to the centre for processing.

Adjacent to the community are houses, a school and several water wells dug into the ground. These wells are walled to capture rainwater from the roofs of the houses, school and community centre.

Figure 4-5: Maysuta community clay preparation (left), old kiln (middle) and mine (right).

4.3.2 The Filtron Ceramic Factory

The clay is broken apart manually and passed through a screen to separate rocks and other large impurities. The community does not have a hammer mill or other mechanical device to break down or process the clay. After sieving, the clay is mixed with water and kneaded on the concrete driveway of the community centre by hand, as shown in Figure 4-5.

The community uses a manual ceramic filter pot press, similar to that used in the Ceramica Por La Paz factory, to create filter pots. The filter press allows the community to create roughly 50 pots in 12 hours, providing they are able to make one pot every 15 minutes, which is a laborious and difficult task in the summer heat.

Prior to the kiln upgrade, the community would have been able to fire only 20-25 CWFPs at once, reducing their production rate. The new kiln, which is known as Manny Kiln, allows up to 100 pots to be fired with less wood and maintains an even temperature throughout the kiln.

The Maysuta community also fabricates bowls, sculptures, cups and ceramic water filters, all by hand. Many of the children in the community create these wares, and were keen to show their clay creations.

Figure 4-6: Photos of the Maysuta community new kiln (left), manual filter press (middle) and CWFP in the kiln after firing (right).

4.3.3 Market and Transport

The Maysuta factory produces filters in low-volume batch orders for the local community and is slowly expanding the size of its operation. Profits from the operation have allowed the community to upgrade its kiln, which will triple the number of filters that can be produced in a given period. The people of Maysuta have also purchased a truck and motorcycle to reach new markets and transport materials needed for production.

Currently, the factory is the only known facility producing CWFPs in the region. The combination of CWFPs and earthenware produced by the Maysuta community has diversified its income and encouraged children in the community to take up pottery.

4.4 Filtron Factory

Figure 4-7: Six brick wood fired kilns at the Filtron factory in Nicaragua.

4.4.1 Plant Description

The largest operation the researcher visited was the Filtron factory, located on the southern side of San Marcos. The Filtron factory was created in response to the Hurricane Mitch, which devastated Central America in 1988, compromising the weakened water infrastructure and leaving millions with no clear source of drinking water (Potters for Peace, 2011). Potters for Peace assembled a factory and manufactured 5,000 CWFPs during the 6 months after Hurricane Mitch. This factory was purchased and moved to its current location, now a commercial-scale operation with an inventory of 7,000 units and weekly production rate of 600-700 filters.

Figure 4-8: The storage area of el filtron (left), the electric clay mixer (middle) and the plant's hammer mill (right).

The Filtron plant obtains its clay from a mine off the southern coast of Lake Managua, near Miraflores, a 43.3-km drive northwest of the factory. The clay is hauled by truck to the factory, where it is broken down by a hammer mill before being passed through a screen and thoroughly mixed using an electric mixer. The plant uses an electrically powered hydraulic press as its primary method for pressing pots into shape, thereby decreasing the time and labour required. The plant does have a manual press on site, as seen in Figure 4-9, along with the hydraulic press and the main CWFP drying rack area.

Figure 4-9: The two hydraulic presses of the El Filtron plant and the CWFP drying racks.

4.4.2 Current Operations

The ceramic water filter factory is located in a privately owned industrial park where several other industries operate. The first and primary business operating out of the park is a palm oil processing plant, which makes palm oil for export. A coffee bean processing and husking facility operates seasonally and produces exceptional coffee, which the researcher confirmed through a first-hand test.

A vermicomposting operation creates high-grade soil that is used to grow the coffee and is also sold off to buyers in the Nicaraguan region. Additionally, the factory has cattle, which provide leather and meat while feeding the worms as well. Employees are trained to work on several aspects of each operation, allowing labour to flow from project to project.

Unlike the Maysuta and Managua factories, the Filtron factory is a commercial operation with larger drying areas as well as inventory storage space containing up to 5,000 complete CWFP kits, which include the plastic receptacle, spigot, user instructions and cleaning pad. Due to the costs of maintaining inventories, the Maysuta and Managua plants did not appear to have the CWFP kit accessories available.

4.5 EcoFiltro, Guatemala

The EcoFiltro factory is located 7 km west of Antigua and 45 km west of the capital Guatemala City, in Guatemala. The privately operated facility is the largest CWFP producer in Guatemala, and was designed from the ground up to maximize work flow, minimize energy use and provide a healthy work environment, as shown in Figure 4-10. EcoFiltro is not associated with PfP, and operates primarily in Guatemala, but is looking to expand into other countries such as Mexico.

Figure 4-10: Interior of the EcoFiltro factory.

4.5.1 Plant Description

EcoFiltro is housed in a large open structure that maximizes the cross breeze in the factory to reduce the drying time of CWFP prior to firing. The factory building is 90m wide by 80m long, housing all aspects of the production process. Like EcoFiltro, the bulk of the space used in the building is devoted to drying filters that have been pressed and storing filters to be tested, packaged and shipped, shown in Figure 4-11.

Figure 4-11: EcoFiltro factory floor and CWFP drying (left), testing (middle) and shipping (right).

In the center of the factory are two natural gas kilns, both capable of firing 450 CWFP in eight hours. Near the back of the factory are the hammer and pug mill, used to process the clay and sawdust prior to mixing as well a dual-loading hydraulic press, which is shown in the center of Figure 4-12.

Figure 4-12: EcoFiltro hammer and pug mill (left), dual CWFP press (middle) and kilns (right).

The hydraulic press has two female molds, one of which is prepped while the other is used by the hydraulic press to create a CWFP. This design maximizes the amount of time the press can be used in a given cycle, halving the production times of Filtron's single loading press. The factory also has two backup manual presses in the event the power is out.

EcoFiltro can produce upwards of 450 filters per day, if running at full capacity. On their factory floor they had roughly 5,000 filters in stock and with several hundred completely packaged with the CWFP receptacle, spigot, instructions, cleaning kit and lid, ready to ship. The factory is setup to run CWFP production runs in large batches, several hundred at a time. The smallest CWFP group they can produce is 450 because that is the required amount that fit in a single kiln.

The building is laid out like a production line, starting with the clay processing in the back, followed by drying and the kilns in the middle. Near the front of the building are large troughs and racks that are used to soak the pots prior to testing their flow rates. Once they pass inspection they are stacked to dry near the shipping and handling area at the front of the building.

4.5.2 Current Operation

During the visit to EcoFiltro on April 1st, 2016 staff were testing the final iteration of a new metal receptacle, adding to the multiple variations in receptacle design they have built over the past six years. Research into the physical design and the materials used to construct the water receptacle and potholder can be seen in Figure 8-2. On the right is the conventional plastic bucket, designed to be affordable and the entry level product at EcoFiltro. The other variations are part of a concentrated effort by EcoFiltro to develop aspirational product models that appeal to a broad range of demographics.

To add further to the design possibilities of each model, the receptacles, as seen Figure 8-2, are decorated by local artists and auctioned off. To raise money for charitable causes and promote their CWFP brand, EcoFiltro is working with famous artists from Guatemala to create one of a kind ceramic receptacles that are auctioning off for $1000.

5 Manufacturing Process

5.1 Materials and Construction

The two primary goals of manufacturing are to produce CWFPs that effectively filter water to remove pathogens and are as simple to manufacture as possible (Potters for Peace, 2011). Ceramic water filters are constructed from clay, a ground combustible (rice husks, saw dust, coffee husks) and water, but can be mixed in a variety of ratios to create filters with different properties. Depending on the geographic region and biome of the factory, each of these ingredients may vary.

5.1.1 Clay

Due to the limited resources of CWFP operations, clay sources acceptable for pot construction are determined based on their physical properties rather than their mineral content. Potters for Peace advises plants to obtain their clay from reliable resources such as brick factories or established clay mines that successfully make earthenware. Non-fired, dried bricks are reliable sources of clay that offer consistent physical properties over time and meet the needs of the filter plant. Such bricks are also cheap and pre-screened, which decreases the overall input cost of filter production.

To reduce the weight and cost, the clay is sifted to remove rocks, debris and organic material prior to transportation. The clay and/or recovered brick is broken down using a hammer mill before passing through a sieve. Factories use different sizes of sieve meshes depending on what is available. Potters for Peace recommends using a 30-mesh screen (0.595-mm opening) to ensure all impurities, sand, gravel and organic material have been removed (Rayner, 2009). This is also a common mesh size that PfP has procured for its factories around the world.

5.1.2 Combustible

A combustible material is mixed with the clay, which burns up when the CWFPs are fired in the kiln. This leaves void spaces within the clay that increase the porosity of the CWFP. Factories have been documented using sawdust, rice husks, coffee husks, paper pulp, millet husks and peanut shells as the combustible. All of these require grinding and sieving before they can be added to the clay, and each type of combustible imparts different qualities to the CWFP (Rayner, 2009).

Factories that use sawdust made from oak have noted reduced flow rates through the CWFPs, and have attributed this to the natural oil in the tree (Rayner, 2009). Sawdust has also been found to cause excessive shrinkage after firing (Ceramics Manufacturing Working Group, 2011). Plant species and the preparation of the combustible material can affect the porosity of CWFPs as well. Factories in Myanmar using rice husk, for example, experienced silica build-up in the pots, which blocked pores and reduced flow rates (Rayner, 2009). Using only the inner husk remedied this problem (Rayner, 2009).

To maintain consistency, factories should use the same combustible material and press it in the same way for every batch. After pulverisation, the combustible material is passed through a sieve to ensure oversized pieces do not enter the production stream, as these have the potential to create large pores and decrease the effectiveness of the CWFP (Servi, Kang, Frey & Murcott, 2013).

As with the clay, PfP recommends using a sieve with a minimum 30-mesh screen (0.595mm) to filter the combustible, although collecting equal quantities of material from sieves 16-, 30- and 60-mesh would provide an equal distribution of particle sizes in the burn out material, which would result in an equivalent distribution of void spaces in the walls of CWFP (Ceramics Manufacturing Working Group, 2011).

5.1.3 Mixing the Clay and Combustible

The dry ingredients – the sifted clay and combustible – are mixed first. Water is when added incrementally while mixing to ensure the right consistency is reached. Ingredient ratios differ across factories based on the mineralogy of the clay in the region and the type of combustible used. Below are five different recipes from four factories that produce ceramic water filters (Rayner, 2009).

Factory	Clay	Burn-Out	Type	Water	Laterite
RDI-C	30 kg	8.2 kg	Rice Husk	12.5 L	2 kg
	30 kg	9.5 kg	Rice Husk	12.5 L	
IDE	26kg	8 kg	Rice Husk	10 L	
Nicaragua	24 kg	2.5 kg	Saw Dust	10 L	
Iraq	50 (vol)	40 (vol)	Rice Husk	30% (weight)	

Table 5.1: Global factory CWFP ingredient mixtures (Rayner, 2009).

Table 5.1 shows the guidelines that require refinement based on the mineralogy of the clay used, the combustible and weather of the region. Potters for Peace has created a manual that leads workers through the process of testing multiple ingredient variations, learning how to fire them and determining the optimal clay/combustible ratio (Potters for Peace, 2011)

RDI-C, a Cambodian based filter producer, adds laterite to the clay. This substance is high in iron content, and has been shown to improve the filter's effectiveness at removing viruses. Laterite also increases the filter's porosity, requiring less combustible material to be added into the mixture (Rayner, 2009).

5.1.4 Pressing the Filter Element

The majority of factories use a filter press with male and female moulds to form the filter element. One factory in Rabinal, Guatemala is reported to use a potter's wheel to hand-form filters, which is not recommended due to the decline in quality control with hand-thrown CWFPs (Ceramics Manufacturing Working Group, 2011). The use of a hydraulic press decreases variability in wall thickness, reduces clay used and removes air bubbles that would otherwise compromise the filter (Ceramics Manufacturing Working Group, 2011).

The mould sets used in the presses at the Nicaraguan facilities were all aluminium, sourced through PfP. They can also be made from cement, cast iron or teak wood.

Potters for Peace recommends using a minimum of a 20 tonnes of pressure to form the pot; less pressure will not achieve consistent wall thickness and may not squeeze air bubbles out of the clay (Ceramics Manufacturing Working Group, 2011). To ease the removal of the filter after pressing, two plastic bags cover each mould. In the Nicaraguan plants, each press had a false bottom in the female mould, allowing the filter to be removed by pushing it from the bottom and pulling it from the top. The plastic bags are removed from the filters and placed on a rack to air dry.

5.1.5 Drying & Firing Prep

Newly formed filter elements often have wrinkles and deformations as a result of being removed from the press. Workers smooth the surface of the pots, straighten the upper lips and ensure the filter walls are square so they align properly with containers and lids. Every pot is stamped with a batch number, which allows it to be tracked throughout the entire process. Each clay batch undergoes pressing, firing and testing together to ensure any defects in the presses can be tracked down and remedied, and all effected pots can be located and destroyed.

Depending on the location and weather, each pot dries for an average of seven days in dry climates and up to 13 days in wet climates (Ceramics Manufacturing Working Group, 2011). Air-drying reduces the water content of the pots while decreasing the energy needed to fire them.

5.1.6 Firing in the Kiln

All pots are fired between 800 and 1000 degrees Celsius, depending on the clay/combustible ratio used and minerals in the clays. Pots are made from one batch of clay and are fired together. Doing so reduces the variance in batch production, thus increasing the factory's capacity to track errors in production and hone production techniques as raw ingredients change.

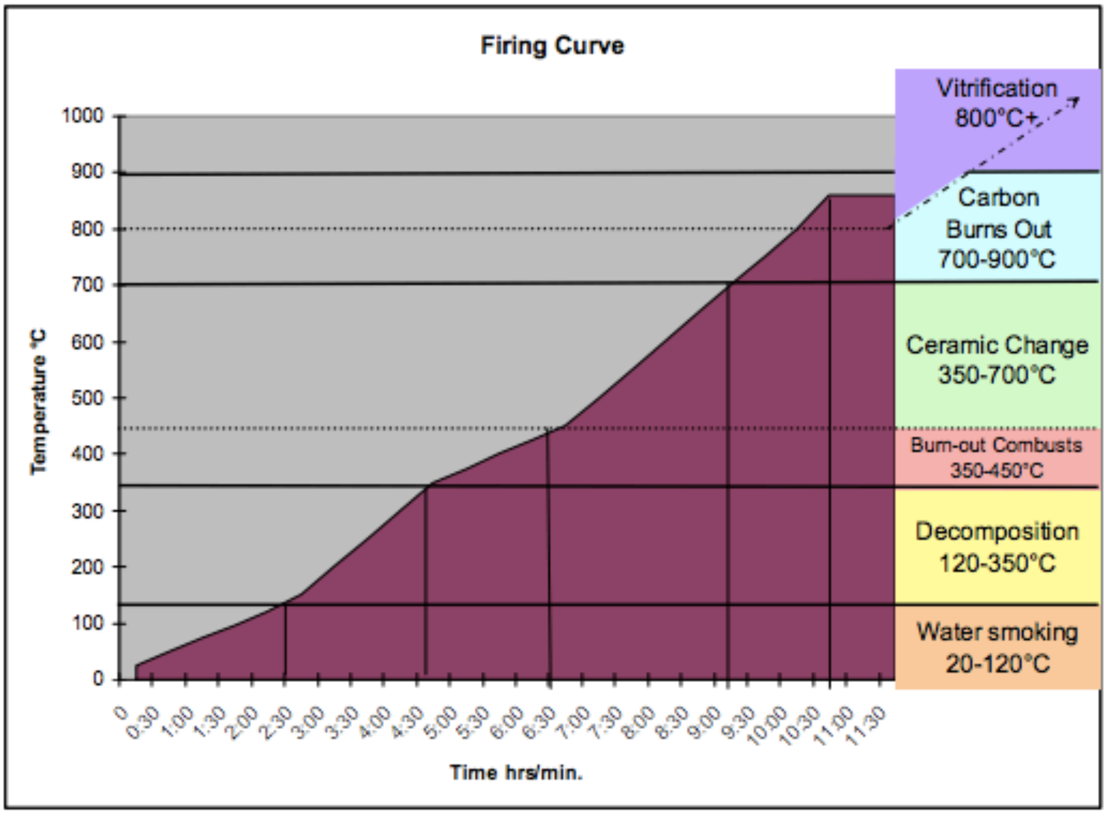

Figure 5-1: CWFP firing schedule in a Kiln (Rayner, 2009).

The firing process ranges in time, depending on the weather and climate as well the skill of the kiln operator (Ceramics Manufacturing Working Group, 2011). Typically, the firing process takes 8–10 hours to go through the six-phases of firing, as seen in Figure 5-1. Post-firing, which is not displayed inFigure 5-1, the kiln is opened slightly and the CWFPs cool to ambient temperature over 12-24 hours, depending on the weather and climate of the factory (Ceramics Manufacturing Working Group, 2011).

Filter cracking can result if the heating times, shown in Figure 5-1, are not followed. In the first phase, rapid heating can turn water trapped in the pores of the filters into steam, bursting the micropores and resulting in the weakening of the filter wall. Rapid cooling of the filters can stress the walls, causing cracks and destroying the filtering capacity of the CFWP.

5.1.7 Flow Rate Testing

CWFPs are designed to be simple to make, and PfP manufacturing guidelines stipulate a rigorous testing procedure to ensure no faulty pots are sold to the public (Potters for Peace, 2011). Previous tests of CWFPs have determined that a flow rate of 2.5 L/hr is optimal to maximise filtration while providing enough water to meet the needs of a family of five (J. Brown et al., 2007; Lantagne, 2001; Potters for Peace, 2011).

To evaluate the flow rate of a filter, it is soaked for 24 hours prior to testing. After the soaking period, each filter is filled with water and tested to determine the hourly flow rate. Filters that pass one litre per hour are discarded for providing insufficient water to the user (Lantagne, 2001). CWFP that provide more than 2 litres per hour may have cracks or larger pore structures that allow high rates of water to pass through the unit, are discarded and suspect of not meeting biological filtration standards (Lantagne, 2001).

5.1.8 Silver Nanoparticle Application

Only after filters have passed quality control are they coated with a layer of silver nanoparticles, also known as colloidal silver. Two methods used to apply colloidal silver to a CWFP are submersing the CWFPs in a silver solution, or painting the solution on to a pot using a paintbrush, both techniques use a 220 mg/L solution of silver nitrate (Klarman, 2009). Potters for Peace recommends painting the 300 mL of 220mg/L solution onto the point, 200 mL on the inside and 100 mL on the outside (Lantagne, 2001).

The liquid colloidal silver permeates the CWFP walls, travelling along the micropores of the structure and permanently adhering to the CWFP walls by binding to the iron minerals in the pot. Lantagne (2001a) found silver is lost from the point and flows into the water, but that it’s primarily from the outside of the pot and in quantities ranging of 30 to 60 ppb in the first run of his trials, followed by approximately 15 ppb in subsequent flow tests.

5.2 Potters for Peace Manufacturing Process

The Potters for Peace recommended manufacturing process of CWFP is shown below in Figure 5-2 as a flow chart (Potters for Peace, 2011). The flow chart tasks are broken into five groups; processes, optional processes, delays, decisions and terminations, provides a breakdown of the entire PfP manufacturing processes and decisions tree.

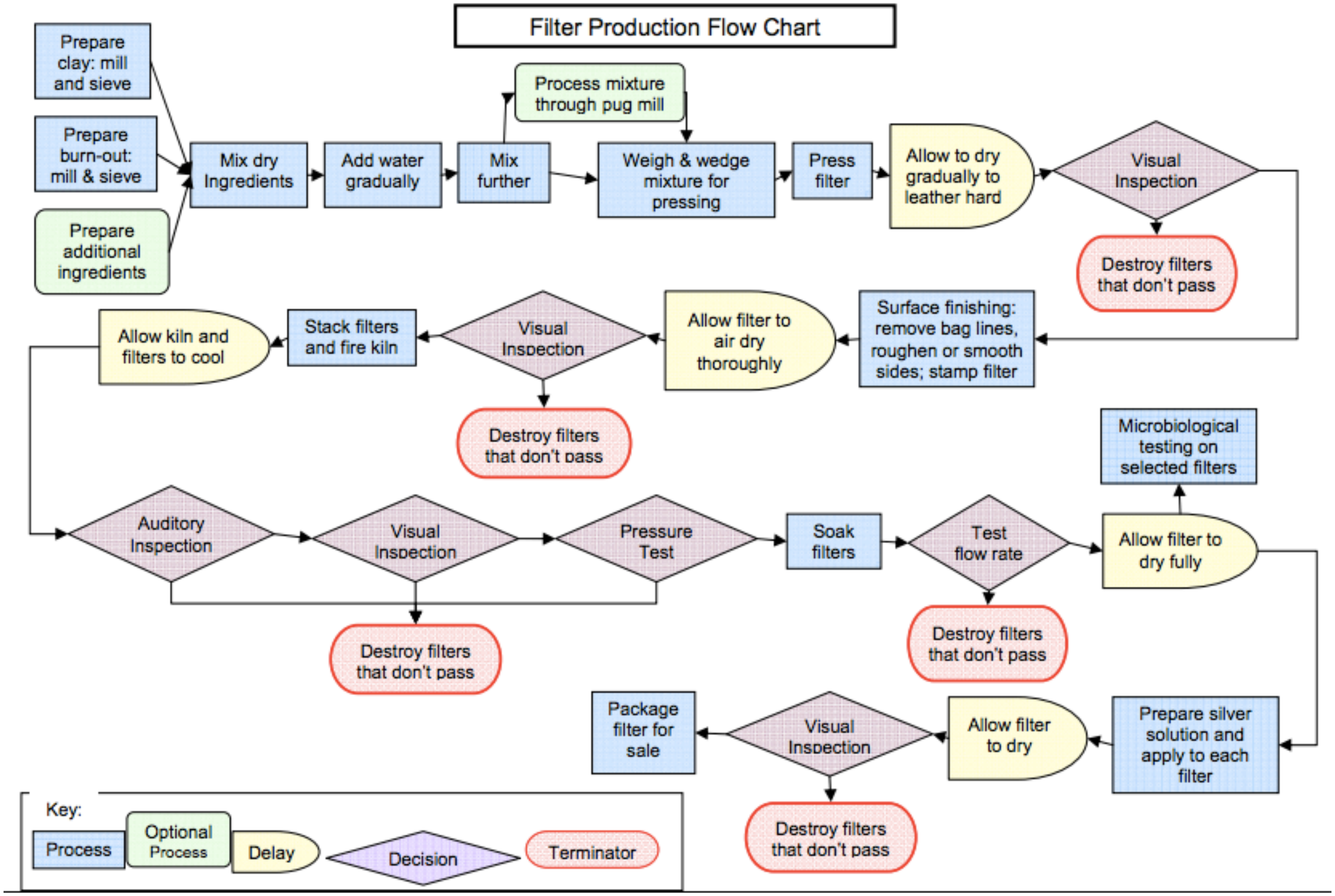

Figure 5-2: CWFP production flowchart and decision tree (Potters for Peace, 2011).

6 Soil Testing

6.1 Material Characteristics

Five clay samples were collected during the December 15th to 20th fieldwork period in 2014. Each sample was gathered by hand, stored in a large ZipLoc bag, labelled and stored in a plastic container protected from moisture and heat. Samples were then transported back to Canada as cargo and stored at 19°C. The clay samples were obtained from two factories: El Filtron and La Maysuta. Three samples were collected from Filtron and two samples from Maysuta, as shown Table 6.1.

Factory	Sample Prep	Location	Notes
1. Filtron	Hammer milled at factory	Factory	This was finally processed
2. Maysuta	From the community mine	Mine	Collected by hand from the end of the mine
3. Maysuta	From the hole in a farm field	Farm	The community collected their clay from ditches dug in farm fields
4. Filtron	Raw Clay Sample	Factory	Collected from a bin storing clay from a local mine
5. Filtron	Raw Clay Sample	Mine	Collected from a bin storing clay from the Northern Mine

Table 6.1: Clay sample and factory information.

Sample 1 was obtained from the Filtron factory, and is the only sample that was collected after passing through a hammer mill. This sample was randomly collected from four locations on a pile of clay. Samples 2 and 3 were obtained directly from the clay mines used by the community to gather its clay for CWFPs and other earthenware. Sample 2 was collected from four different regions along the mine cliff face, while Sample 3 was collected at four different locations along a trench that the Maysuta community used to mine clay. Sample 4 is a non-processed version of Sample 1, gathered from a storage bin at the Filtron facility by randomly selecting from four places around and within the pile. Sample 5 is a raw clay sample from a different mine than the first three samples, located West of Managua.

6.2 Test Methods

6.2.1 Index Testing

To assess the physical properties of the clay samples, the liquid and plastic limits of the clays were examined, along with the particle sizes of the samples. American Society of the International Association for Testing and Materials (ASTM) methodologies were followed for all Atterberg limit testing of the clay samples. Prior to testing, all samples were stored in a humidity-controlled room at 19°C. The samples were then broken down using a mortar and pestle before sieving and further processing.

Physical Properties Testing	Methodology
Liquid Limit	ASTM D4318 - Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
Plastic Limit	ASTM D4318 - Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
Particle Size Distribution	ASTM D422 - Standard Test Method for Particle-Size Analysis of Soils

Table 6.2: Clay testing protocols.

All procedures listed in Table 6.2 were conducted by the researcher in the Coal Processing Laboratory building of the Mining Engineering Department of the University of British Columbia.

6.3 Sample Selection and Splitting Methods

To reduce variance in the results, each of the five samples were split into four using a riffle-style sample splitter. For smaller samples, such as those analysed using XRD, 10 grams of sample were selected by splitting spreading the sample onto a grid and selecting an equal portion from each region to create a representative sample.

6.3.1 X-Ray Diffraction

To assess the mineral content of the samples, each was analysed using X-ray diffraction by the University of British Columbia Department of Earth, Ocean and Atmospheric Sciences X-ray diffraction laboratory. All samples were ground in ethanol in a McCrone Micronising Mill for 10 minutes prior to being loaded into a testing bed for analysis. Each sample was scanned with CoKα radiation on a Bruker D8 Advance Bragg-Brentano diffractometer equipped with Fe monochromator foil.

The X-ray diffractograms were analysed using the International Centre for Diffraction DatabasePDF-4 and Search-Match Software by Bruker and the X-ray powder-diffraction data was refined using the Rietveld program Topas 4.2 (Buker AXS).

7 Results

7.1 Introduction

This chapter reviews the findings from the laboratory analysis of the clay samples collected. These findings are outlined in section 6.2. Later in the chapter, additional data is included from the research of Duocastella and Morrill (2012).

7.2 Plasticity

The plasticity index describes the behaviour of a material based on two functions: the liquid and plastic limits calculated as percentages of the soil's moisture content, plotted on a graph. The plastic index results of the five clay samples tested are shown in Figure 7-1. The A-line is plotted to lay parallel to established soil characteristics separating inorganic clays, which lay above the A-line, from sediment-rich silts falling below the A-line.

The majority of the samples – 2 through 5 – straddle or lie just below the A-line, indicating that these clays are low-plasticity silt (ML). Sample 1 from the Filtron Factory is the only clay to have all four sub-samples above the A-line. Sample 2 from the clay mine in Maysuta is a silty-clay of medium plasticity. The second Maysuta sample, Sample 3, is also a silty-clay, appearing to be slightly less plastic than Sample 2. Samples 4 and 5 are silty-clays as well.

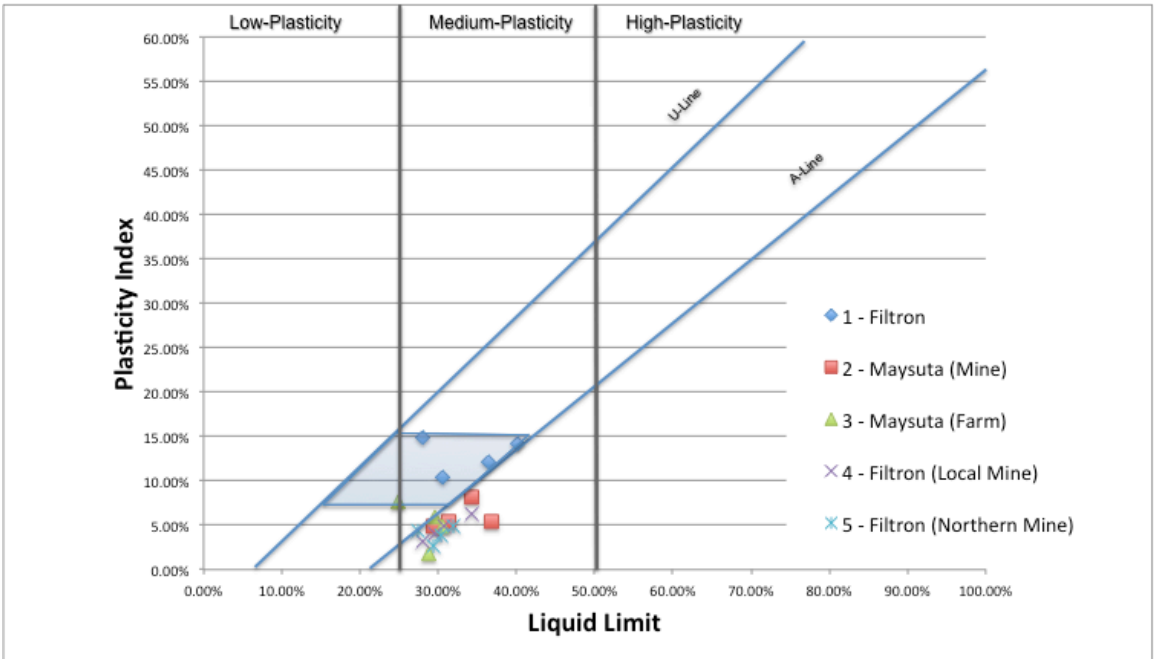

Figure 7-1: Plasticity index graph describing soil characteristics.

7.2.1 Particle Distribution

The particle size distribution shown in Figure 7-2 is the combination of the sieve grain size analysis and the hydrometer particle size analysis. Samples 2 and 4 have higher proportions of silt than the other samples, and Sample 2 has the highest proportion of clay size particles. All samples have similar size proportions of sand until examining particles that are smaller than 0.1mm. Samples 3, 4 and 5 contain less than 3% of particles smaller than 0.001mm and 0% smaller than 0.0001mm.

Sample 4 from the Filtron factory shows a drop in the proportion of particle size at 0.001mm. While not as pronounced, Sample 2 also displays a drop in the percentage of particles within the tail end of the silt size range.

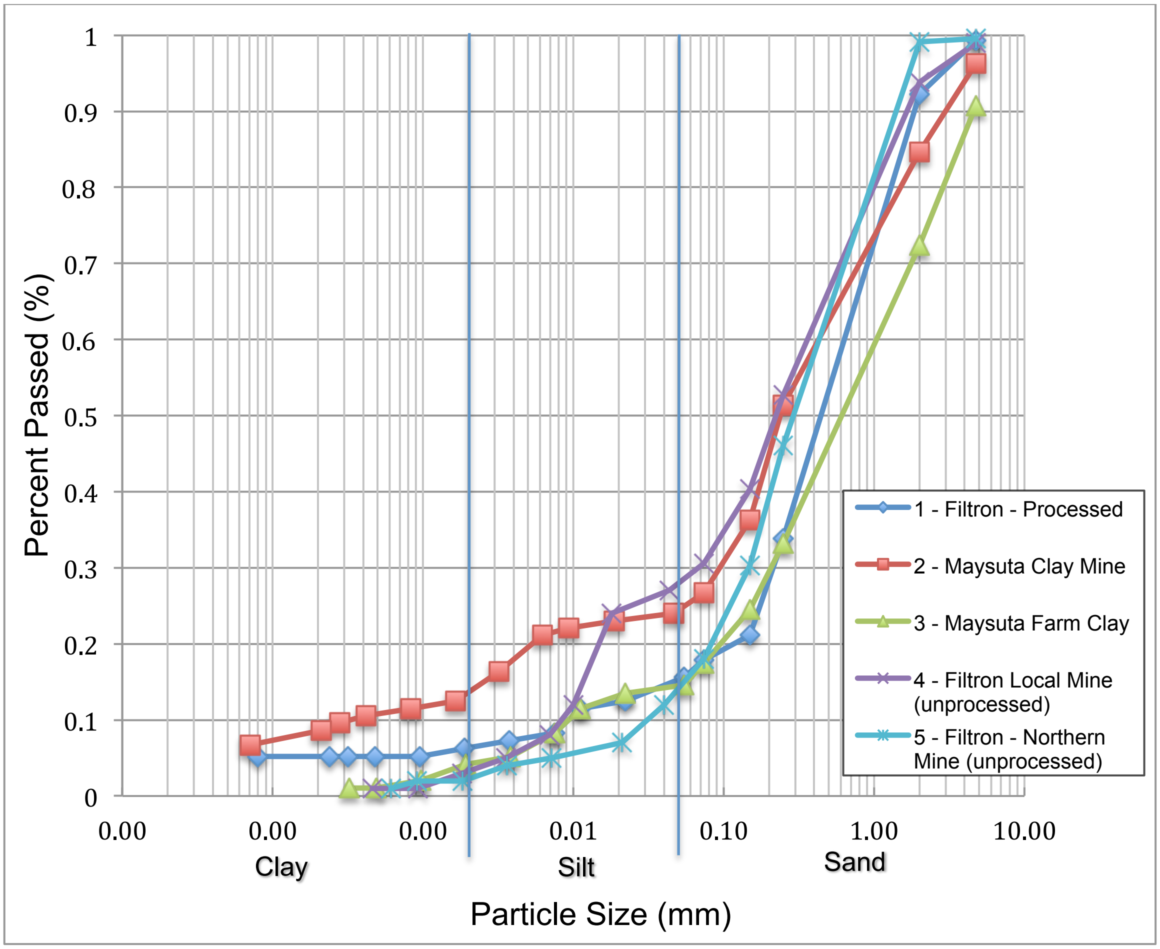

Figure 7-2: CWFP sample grain size analysis.

7.2.2 Particle Size Comparison to PfP Data

Potters for Peace has published data from six CWFP factories operating in different countries around the world (Duocastella & Morrill, 2012). Each sample was prepared following the ASTM D422 guidelines. Nine samples in total from PfP are plotted alongside the data from this study in Figure 7-3.

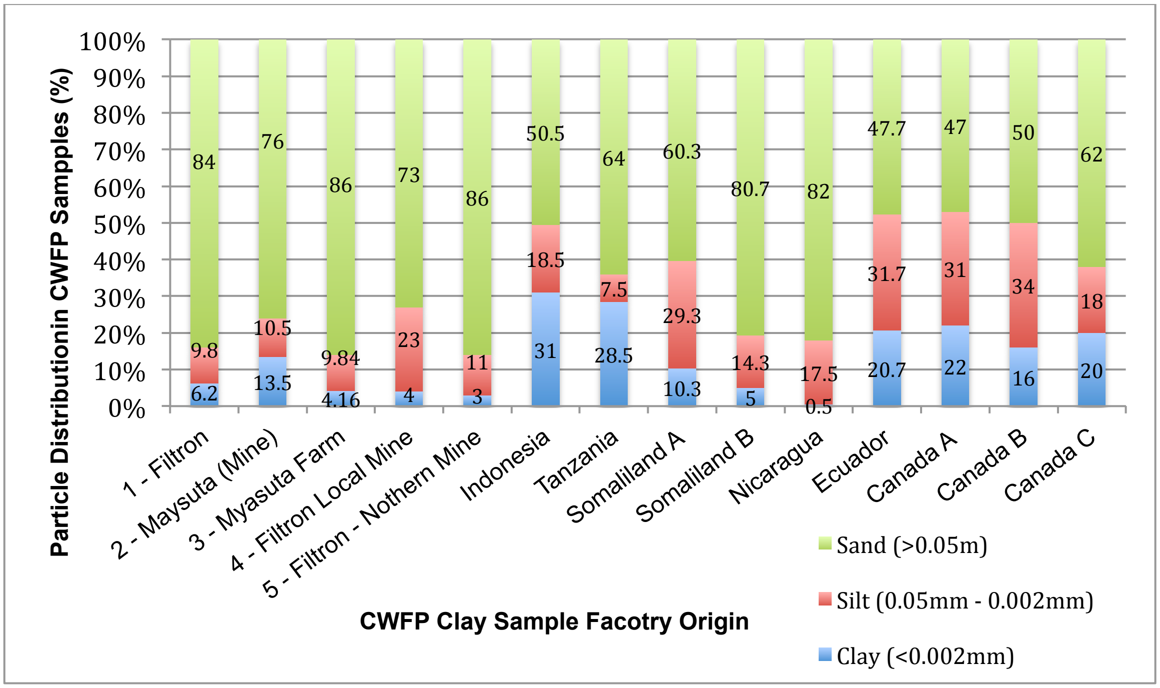

Figure 7-3: Particle size comparison of CWFP clay sample materials across global factories (Duocastella & Morrill, 2012).

Within this dataset, Sample 2 has the highest proportion of clay minerals at 13.5%, followed by Samples 1, 3, 4 and 5, which has the lowest clay composition at 3%. All samples contained more than 72% sand.

The variation in soil types amongst the PfP study samples is broad, as clay values range from 0.5% in Nicaragua (which is far below the five-sample test group in this study) to 31% in Indonesia. Overall the majority of the samples contain large quantities of sand, representing over 60% of total composition.

7.2.3 Soil Texture

To further evaluate the soil properties of the samples of both studies, these are plotted on a three-axis plane according to the percentage of relative sand, silt and clay composition. All samples from this study are classified as loamy-sand, as are the Nicaraguan and Somaliland sample B. The remaining samples from the PfP study are classified as sand-clay-loam (Tanzania, Indonesia and Canada C) and loam (Ecuador, Canada A and Canada B) (Duocastella & Morrill, 2012).

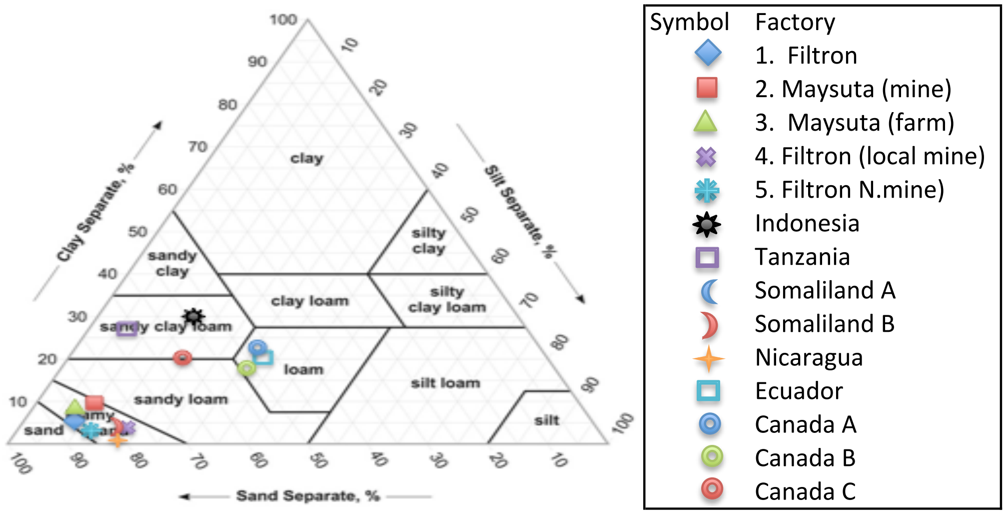

Figure 7-4: Soil texture plot contrasting samples 1-5 from this study and potters from peace samples from previous studies (Duocastella & Morrill, 2012).

7.3 X-Ray Diffraction

#1 & 5 - Filtron		**#2 - Maysuta (Mine)**		**#3 - Maysuta (Farm)**		**#4 Filtron (Local Mine)**	
Mineral Type	%	Mineral Type	%	Mineral Type	%	Mineral Type	%
Quartz	25.7	Quartz	55.3	Quartz	40.1	Quartz	22.8
Plagioclase	34.6	Hematite	0.5	Illite/Muscovite	30.5	Plagioclase	32.4
Tridymite	4.1	Kaolinite 1A	30.4	Plagioclase	14.3	Hematite	4.2
K-feldspar	3.7	Anatase	0.8	Kaolinite 1A	4.8	K-feldspar	8.8
Cristobalite	3.6	Montmorillonite	13.1	Hematite	1.4	Cristobalite	3.3
Hematite	2.3			Rutile	1.3	Tridymite	3.0
Dolomite	1.6			K-feldspar	2.2	Illite/Muscovite	7.2
Calcite/magnesian	0.9			Montmorillonite	5.5	Magnetite	1.0
Montmorillonite	23.5					Montmorillonite	17.3
Clay Minerals	**27.1**		**43.5**		**42.9**		**33.2**

Table 7.1: X-Ray diffraction mineral composition of CWFP clay building materials.

In the X-ray diffraction test, summarized in Figure 7-1, Sample 2 has the highest percentage of clay minerals, consisting of 30.4% kaolinite and 13.1% montmorillonite. Sample 3 has the second-highest clay composition, containing 30.5% illite/muscovite, 5.5% montmorillonite and 4.8% kaolinite.

All samples are composed of a minimum of 5.5% of montmorillonite, but Samples 1 and 4 contain the highest amounts at 23.5% and 17.3%, respectively.

8 Distribution & Marketing

8.1 Introduction

This chapter reviews the operational states, production protocols and locations of factories working with PfP to produce CWFPs. In a broader context, PfP marketing and distribution practices are contrasted with other non-PfP affiliated factories: EcoFiltro in Guatemala and RDI in Cambodia. Finally, the marketing strategies used to promote CWFP products both regionally and nationally are discussed, specifically in relation to populations in need of CWFPs and the complexities of reaching these people.

8.2 PfP-Associated Factory Locations

Potters for Peace does not own or operate CWFP factories; instead, the organisation actively promotes ceramic water filtration technology in communities by providing access to open-source material on all aspects from start-up, operations, marketing, manufacturing and technical support. Potters for Peace has supported the creation of over 50 factories globally, which together have manufactured over 1 million CWFPs serving up to 6 million people.

Figure 8-1: Known factory locations of plants that have worked with PfP (Potters for Peace, 2016).

The factories that are currently or have been affiliated with PfP are presented in Figure 8-1, which has been modified from the organisation's website. In total, 46 factories are listed and categorised into four groups based on their production status, current protocols and whether they are in contact with PfP.

Map Icon	Factory Status	Quality Control & Protocols
Green	Full production	Follows protocols closely
Yellow	Partial production	Follows protocols closely
Purple	Partial production	Outside protocols and in communication with PfP
Red	Unknown	Out of communication

Table 8.1: PfP global factory operating protocol status.

The majority of factories are located in countries that have been selected by the UN as regions in need of water interventions, particularly in rural undeveloped areas (United Nations, 2015). The factory distributions amongst South and Central America, Africa, the Middle East and Asia are highlighted in Table 8.2.

Category	Total	South & Central America	Africa	Middle East	Asia	% of Total
Green	**14**	2	7	1	4	30.43%
Yellow	**8**	3	4		0	15.22%
Purple	**7**	1	2	1	3	15.22%
Red	**18**	8	1		9	39.13%
Total	**46**	**14**	**14**	**2**	**16**	

Table 8.2: PfP global factory count by region and operational status (Potters for Peace, 2016).

The Middle East has only two factories: one in Yemen that is following protocol, and the other in Pakistan that is communicating with PfP but not currently following PfP protocols. One facility that is listed on the map, but omitted from the chart, is in Western Canada. This is the headquarters of Potters Without Borders and is not a factory, but a testing facility. According to PfP, 29 of the total 46 CWFP factories (63%) are operational, but only 22 plants (30.4%) are currently operating and abiding by PfP protocols.

8.2.1 Factory Capacity to Reach more People

To increase production and reach the estimated 783 million people lacking clean drinking water, current factories must expand production and/or more factories are needed. Developing larger CWFP factories has three limiting problems:

1. Large factories producing high volumes of CWFPs need larger local markets (urban areas) and have higher start-up costs.
2. Shipping costs of fragile CWFPs, specifically in rural undeveloped areas where roads are not maintained, may increase breakage and become cost-prohibitive to centralised high-volume factory models.
3. Factories producing high volumes of CWFPs exclusively are at a higher degree of risk with respect to cultural, political or demand-related shocks that may affect the capacity of the market to purchase those products.

There is a strong case for developing larger factories to serve urban residences. In 1985, Mexico City suffered an earthquake that severely damaged the city's water distribution infrastructure, causing thousands of tiny leaks which lost approximately 1,000 litres of treated fresh water per second (Castro, 2006). Each leaking point is a source of contamination to water in the system, which can mix with groundwater tainted by agricultural, industrial and other biological contaminates (Castro, 2006).

Damaged infrastructure, low fresh water sources (aquifers and rivers) and an increased demand from a growing population have resulted in water shortages in Mexico City (Castro, 2006). To supplement their needs, individuals who cannot afford to purchase bottled water collect it from non-protected sources such as dugouts, rainwater and small streams where available – all of which can also be contaminated (Castro, 2006).

Mexico City is one example of a location where a large centralised factory could operate successfully based on the market size, the need for point-of-use technologies to augment current infrastructure and the number of those who cannot afford bottled water.

Reaching low-density rural populations requires larger transportation distances and/or the creation of more factories that produce lower volumes of pots to meet the local market demand. The Maysuta plant in Northern Nicaragua is an example of a small factory that began by serving only the local community, but has grown with the market as more people see the benefits of using CWFPs to treat their water.

Regardless of size, all plants require marketplaces that trust CWFP technologies over other options such as bottled water, and are willing to treat and consume their local water supply. Even in a marketplace where 783 million people do not have access to clean water, these people will not accept a foreign technology or practice that is inconsistent with their cultural norms. Changing daily rituals of how water is gathered, treated and consumed requires a social marketing campaign to educate people about why it is important, how it can correctly be done and what benefits they will receive from adopting this new behaviour.

8.3 Social Marketing

Social marketing is the 'application of marketing knowledge, concepts, and techniques to enhance social as well as economic ends' (Gordon, 2011). Ceramic water filter pots are designed with the express purpose of increasing social and economic well-being, but their adoption requires changing the cultural and social norms of the poor who are in need of clean water. In his 2008 paper, *Marketing Safe Water Systems,* Urus Heieri highlights five obstacles that prevent the widespread adoption of CWFPs, as well as other point-of-use water purifying technologies (Heierli, 2008). Heieri's five obstacles are:

1. <u>No direct link between unsafe water and health</u>: It is impossible to detect water contamination with the naked eye. Clear pristine water that appears safe could be just as contaminated as turbid muddy water. Tracking what did or did not cause disease is difficult, particularly when the symptoms can arise hours later.
2. <u>No single cause-effect relationship between water and disease</u>: Individuals can contract diarrhoea from a range of sources, including poor hygiene, contaminated food or dishware, or consuming water that was improperly purified. Only when an individual removes all sources of contamination is it possible to dramatically reduce the incidence of diarrhoea.
3. <u>Cultural adoption of basic hygiene and education of self-healthcare</u>: Changing ingrained social habits can take generations, and education alone will not shift culturally instilled behaviours. Individuals living in societies where hygiene is expected, especially among the middle class, are more likely to adopt such social

behaviour. Those living in impoverished conditions accept a different social contract, where less is expected of their personal hygiene.

4. Ambition is more effective then rational marketing: Social factors such as prestige, honour and social status create strong incentives for individuals to change. Marketing products such as CWFPs as aspirational is more effective than a campaign aimed at the poor.
5. Sustainable adoption requires a sustainable supply chain: People will use a product when it is readily available, convenient and long-lasting. Products that are distributed by NGOs on a one-time basis do not offer long-term support or spare parts when something breaks.

Heieri states that the first three problems hindering widespread acceptance of a new cultural norm are related to the entrenchment of previous habits. Without long-term, consistent marketing, education and pro-habit forming protocols, it is unlikely that people will adopt a new behaviour on their own. The last two problems described by Heieri are strictly marketing issues: What is the consumer's perception of the product, and can the supply chain meet consumer demand? The next section discusses the strategies used by Potters for Peace in Nicaragua and EcoFiltro in Guatemala to solve the following problems:

1. The perception of water with regard to an individual's or community's self-image, and how does this affect long-term adoption of CWFP technologies.
2. The market conditions where CWFPs are sold, specifically the size, level of income and education of CWFP consumers

8.3.1 Potters for Peace

Potters for peace utilises a passive method of promoting CWFPs, which is based on word-of-mouth marketing by the communities it has worked within the past, open-source access to technical expertise the organisation has accumulated, and attendance at conferences and meetings with other water organisations and professionals. The PfP model does not aim to 'win over' individuals who do not believe in the benefits of CWFP use, nor does it depend on the success and sale of CWFPs.

Potters for Peace does not spend its time and energy on convincing people to use or manufacture CWFPs; rather, PfP directs its energy toward groups that have approached the organisation for help. Furthermore, PfP does not assist in the financing of any new projects and requires that all new factories raise their own capital. Instead, PfP focuses on social entrepreneurship through the empowerment of local people. Factories are created to make a profit, with the goal of sustaining the project as well as the filter manufacturing team in the long term.

This methodology increases the likelihood that the groups PfP works with are proactive, health-conscious and willing to change, which is indicative of the 63% success rate for CWFP factory start-ups. However, by approaching groups passively, PfP's growth rate has been slow. Over the last 18 years the organisation has assisted in the manufacturing of approximately 55,000 filters per year. At this rate, it would take nearly 2,300 years to meet the needs of the 768 million people in need of clean water, assuming each filter was used by a family of six.

While the Potters for Peace's approach has made the organisation a recognised authority on CWFPs from a technical perspective, is not a suitable model for bringing water to those in need by the end of the Sustainable Development Goal period of 2030. Meeting this goal will require roughly 9.1 million new filters per year.

8.3.2 EcoFiltro

Located west of Antigua, Guatemala, EcoFiltro is one of the most successful CWFP operations in the world, in this researcher's opinion. The success of EcoFiltro's marketing and sales platforms is measured by two metrics: market penetration, and the success in changing the view of CWFPs from simple water filters to an aspirational product that anyone would be proud to have in their home.

8.3.3 EcoFiltro Market Strategy

During a three-week trip to Guatemala, the researcher found EcoFiltros in nearly every restaurant, pharmacy, hotel, school and church throughout the areas visited. Unlike the Nicaraguan factories, EcoFiltro has created a broad range of filter receptacles in cooperation with local artists and design groups. The diversity in designs of CWFP exteriors can be seen in Figure 8-2, which shows six CWFPs made from a variety of materials such as plastic, acrylic, metal and clay. Despite the exterior the filter is still the same as for the total clay container.

Figure 8-2: EcoFiltro external water receptacles for CWFP of various designs (metal, clay and plastic).

The low-cost plastic bucket design model for a CWFP, shown on the far right in Figure 8-2, is a common design around the world. This design has been described as looking like a ‘garbage can’, which is one of the chief criticisms facing CWFP adoption. EcoFiltro’s ongoing investment in new designs aimed at creating aspirational products has shifted Guatemalan consumers’ perception of the CWFP from a simple water filter to a status symbol. In doing so, EcoFiltro incorporated culturally desirable attributes into the external receptacle that changed its primary characteristic from a filter into a piece of art. McCraken (1986) stated that when consumer goods carry a cultural meaning, they follow a three-step process that transfers a message from a culture to a product, and eventually to the consumer.

Designers, producers and advertisers rely on established cultural norms that they ‘transfer’ to products, attracting individuals who want to be associated with that cultural message (McCracken, 1986). The consumer who identifies with the cultural message purchases the product, and in doing so, the cultural message is transferred to the consumer from the product (McCracken, 1986). This transfer can only occur within a community that shares similar ideologies and aspirations.

EcoFiltro’s reinvention of the water filter is not a new idea. Several other agencies, such as PACT and RDI for example, have created new water filtration exteriors to change the public’s image of CWFPs. EcoFiltro has not created a new exterior, but has rather found a common cultural thread for Guatemalans that speaks to their values regarding health, community stewardship, environmental awareness and simplicity.

8.3.4 EcoFiltro Sales Strategy Breakdown

EcoFiltro created a product that consumers want, but a secondary problem was educating the consumers on why they would want it, how they could buy it and why it would benefit them. To reach as many people as possible and support local communities, EcoFiltro supplied Guatemalan classrooms with CWFPs and created a programme aimed at making the filters affordable to families. This programme is summarised in Figure 8-3.

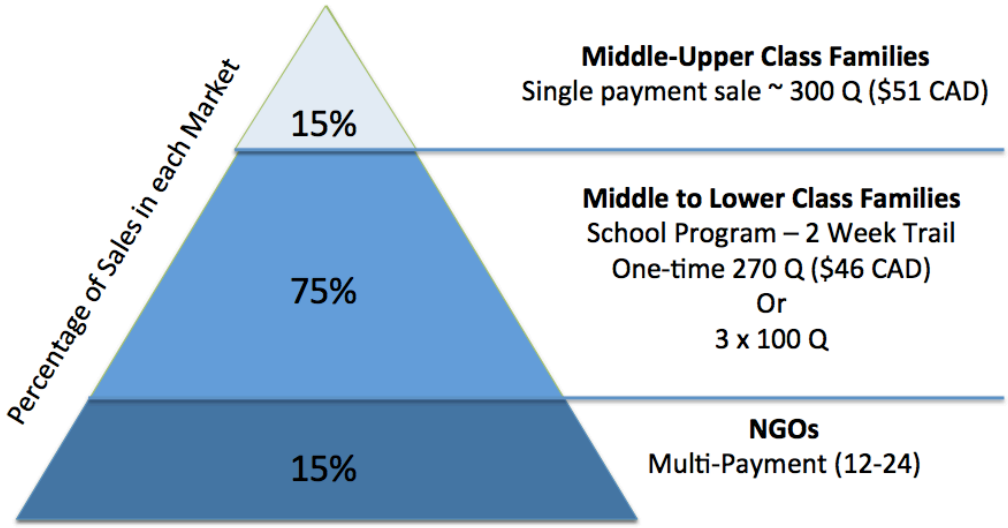

Figure 8-3: EcoFiltro sales pyramid as seen at their head office in Antigua, Guatemala.

EcoFiltro broke the Guatemalan CWFP marketplace into three segments, each with a specific payment plan and consumer in mind. Market research indicated that most Guatemalan residents would not purchase a CWFP if the cost was more than 300 Quetzals ($51 CAD). Individuals who purchased the CWFP through the school using a one-time payment paid only 270 Quetzals, while those who used the 3-month payment plan paid the full price, but with payments spread over a longer period of time.

The bulk of sales (75%) are from the school programme, followed by more affluent consumers (15%) who can afford to purchase the filters outright at full price. The final group at the bottom of the pyramid in Figure 8-3, NGOs, make up 10% of total sales and are under contract to sell CWFPs at a given price. They can change the pay period, but cannot give the filters away, as this is an act that would erode the value of CWFPs in other markets and hurt the EcoFiltro business model.

Figure 8-4: EcoFiltro clay CWFP receptacles designed by local Guatemalan artists.

Within six years EcoFiltro has become a dominant name in water filtration in Guatemala, and there is much more to learn about how the company conducted its research and designed, tested and created its CWFPs. Currently, EcoFiltro is developing new product lines and working with artists to create one-off CWFP receptacles to be sold at auction to raise money for other charitable projects. Figure 8-4 highlights a sample of the exterior receptacle artwork that is being painted onto CWFP receptacles.

9 Discussion

9.1 Physical Properties of Clay Samples from PfP Factories

The clay samples analysed in this study were collected from the Maysuta and Filtron facilities, both of which are fully operational factories that produce filters in accordance with the best practice guidelines for CWFP manufacturing (Ceramics Manufacturing Working Group, 2011). These facilities are recognised by PfP as best-case examples of CWFP production in Nicaragua, which means that the clay falls within the upper and lower tolerances of plasticity, shrinkage, porosity and durability required to create a CWFP. The first part of this chapter discusses the physical testing results and how they impact production of CWFPs. The second part of this chapter contrasts the marketing models used between the three factories (Maysuta, Filtron and Old Managua) and compares the PfP model with that of Guatemala-based EcoFiltro.

9.2 Exploration of the Physical Properties of Nicaraguan CWFP Factory Clay Samples

9.2.1 Lower Limits of Clay Content for CWFP Production

The physical properties of the clay collected in this study describe clay material that is suitable for the construction of CWFPs. Figure 7-3 describes the proportion of clay, sand and silt in this study's five CWFP clay samples and the nine other samples from six different factories. The clay content of all the samples ranges from 0.5% in a sample collected from a Nicaraguan clay mine to 31% from the Indonesian factory sample. The Nicaraguan sample containing only 0.5% was obtained from a PATH study on ceramic water filters (Duocastella & Morrill, 2012), and was suspected to show a collection error resulting in a low quantity of clay. Filters that were made using this clay failed to pass PfP standards. This establishes a failure limit with regard to the proportion of clay required in a sample to construct viable CWFPs, although more information is needed to determine the mineralogy and physical properties of this lower limit.

The sample collected from the Northern clay mine used by Filtron had the lowest proportion of clay content measured in this study at 3%. It can be postulated that the lower limit of clay content required for CWFP production is between 0.5% and 3.0% for a set mineralogy (in this case, Nicaraguan). As the clay content decreases, so does the plasticity of the clay, which is a critical property of clay used in pottery to be moulded and shaped.

9.2.2 Upper Limits of Clay Content for CWFP Production

With the data from this study and that of Duocastella and Morril (2012), it is not possible to establish an upper limit for clay content at which a CWFP would not meet the production guidelines laid out by the Ceramics Manufacturing Working Group (Ceramics Manufacturing Working Group, 2011). Nevertheless, it can be argued that an upper clay content limit does exist for CWFPs, depending on the clay minerals present, such as montmorillonite, which has been shown to have an upper limit when used in CWFP production.

To maintain a minimum flow rate of two litres per hour, the porosity of a CWFP's wall structure must maintain a minimum hydraulic conductivity (Lantagne, 2001c; Yakub, Du & Soboyejo, 2012).

Material	**Particle size**	**Conductivity**
Units	mm	m/d
Coarse gravel	16.0-32.0	860-8600
Medium gravel	8.0-16.0	20-1000
Coarse sand	0.5-1.0	0.1-860
Medium sand	0.25-0.5	0.1-50
Fine sand	0.125-0.25	0.01-40
Clay	<0.0004	<0.001

Table 9.1: Hydraulic conductivity of various soil types (Charbeneau & Sherif, 2002).

Table 9.1 outlines the hydraulic conductivities of typical gravel, sand and clay soils in metres per day, highlighting that as the particle size of a material decreases, so does its hydraulic conductivity (Charbeneau & Sherif, 2002).

Holding the particle size and quantity of sawdust static, the quantity of clay within a sample that reduces the flow rate of water through a CWFP to less than 2.5 litres per hour could be defined as the upper clay failure limit for a CWFP. This is assuming that no other failures occur as the clay composition is increased to this technical failure limit, aside from the effects of montmorillonite, which leads to cracking if present in high enough quantities.

9.2.3 Effects of Clay Sample Processing

Of the five clay samples obtained, three samples (1, 4 and 5) were collected from the Filtron factory during the December 2014 field visit. These samples were sourced from two different clay mines:

- Sample #1 Filtron Northern Mine   Processed in a hammer mill and sieved
- Sample #4 Filtron Local Mine   Raw Sample
- Sample #5 Filtron Northern Mine   Raw Sample

Samples 1 and 5 were gathered from the same clay mine source, with the only difference being that Sample 1 was production-ready, having been processed in a hammer mill and passed through a sieve.

Comparing the particle size distributions of the raw Sample number 5 (86% sand, 11% silt, 3% clay) to Sample 1 after processing (84% sand, 9.8% silt, 6.2% clay) shows a decrease in sand and silt along with an increase in the percentage of clay. This may be the result of removing a portion of the larger material during the sieving process, which increases the proportion of clay compared to the raw Sample 5.

The effect of processing the sample is apparent in the plasticity index, shown in Figure 7-1, where Sample 1 is the only sample classified as inorganic clay (CL). All other samples, including Sample 5, fall below the A-Line of the plasticity index and are classified as low-plasticity silts (ML).

The increased plasticity of Sample 1 may be due to the increased proportion of clay in the sample. Sample 2, however, contains over twice the percentage of clay (13.5%) as Sample 1, yet falls below the A-Line and has a lower plasticity. When compared to the XRD findings, these results show a similar discrepancy in clay compositions.

In the XRD analysis Sample 1 contains 27.1% clay, the majority of which is classified as montmorillonite (23.5%). The XRD report for Sample 2 found there to be 30.4% kaolinite and 13.1% montmorillonite, for a combined total of 43.5% clay.

This may be the result of clay forming micro-aggregates in the samples, which in the case of Sample 1 were broken apart during processing. Although all samples were processed using a mortar and pestle prior to use in this study, Sample 1 would have experienced significantly more mechanical separation than the other four samples, potentially increasing the percentage of smaller material present.

As mentioned above, Sample 5 has a high percentage of sand. In the particle size distribution curve, Samples 1 and 5 cross at the 0.07-mm mark. Sample 1 has a larger proportion of material below 0.07mm than Sample 5, and more particles falling below 0.01mm than Samples 3, 4 and 5. Sample 2, which was discussed as having large quantities of clay, has the highest proportion of fine particles smaller than 0.02mm.

If the differences of plasticity are the result of processing using mechanical means, this is an important factor to consider for facilities that do not have access to mechanical grinding and separation equipment. Most facilities have access to the screens with a mesh size of 30 (0.595mm) to select their material, but not all factories have access to electrical equipment such as hammer mills (Rayner, 2009).

The Maysuta CWFP factory does not have access to mechanical separation machinery, although the community's clay source is significantly more abundant than that of the Filtron mines.

9.2.4 Presence of Montmorillonite

Montmorillonite is a problematic mineral to have in large quantities when manufacturing ceramics. Montmorillonite's capacity to swell in the presence of water and shrink as it dries creates stress on the walls of CWFPs as they dry, often leading to cracking or breakage (Norton, 2016). This mineral is also known to be highly plastic, and when mixed with other clays in small quantities, its presence goes unnoticed. Exactly what constitutes a small quantity remains to be determined. The XRD analysis shows that all samples in this study contain between 23.5% and 5.5% montmorillonite, as summarised below.

- Sample #1 = 23.5%
- Sample #2 = 13.1%
- Sample #3 = 5.5%
- Sample #4 = 17.3%

Sample 1 is classified as clay and contains the highest quantity of montmorillonite, which may contribute to the high plasticity of the sample. This sample, which is from the Filtron factory, is currently used to make CWFPs that pass inspection and show no signs of cracking. Under the given conditions, the current upper limit for montmorillonite to be used in CWFP production is greater than 23.5%.

It should be stated that the XRD analysis is not without its limitations. The montmorillonite detected by XRD analysis may be a mixture of other clays, such as interstratified chlorite-smectite and potentially trioctahedral vermiculite and nontronite (Timmermans, 2015; Velde, Bruce B, 2014). The quantitative XRD analysis in this case may over-estimate the quantity of montmorillonite in the samples. X-ray diffraction of impure smectite samples requires glycolation to expand the stratified layers, which are disturbed from weathering (Sakharov, Lindgreen, Salyn & Drits, 1999; Srodon, 1980). Depending on the charge density and cations between the stratified layers of clay, as well as the humidity and other factors that may influence the expansion of each clay layer, the XRD analyses of smectite mixed clays have a margin of error of up to 30% (Srodon, 1980).

These experimental errors suggest that the quantity of montmorillonite in Samples 1 through 4 could have been over estimated by as much as 30%, according to the findings of Srodon (1980). This places the acceptable upper limit for montmorillonite used in CWFP production between 16.5% and 23.5% by weight, with respect to the mineralogy and physical properties of these samples.

9.3 Contrasting the Marketing and Distributing Models of PfP Factories and non-PfP Related Facilities

Potters for Peace does not own or operate CWFP factories. Instead, it provides support, guidance and technical assistance to organisations and individuals all over the world who are interested in starting and running a CWFP factory. The organisation accomplishes this by offering all the necessary information – in the public domain as open source – to start, run and operate a factory, as well as providing technical assistance with materials, production and marketing issues.

Potters for Peace does not collect royalties from factories, and the growth of the organisation is not linked to the success of any one factory. With no direct financial flow from its efforts, other than payment for direct site visits, PfP relies on grants and donations to meet its annual operational budget needs. Doing so allows the organisation to operate in regions with multiple factories without creating a conflict of interest, as PfP is not aligned with the interests of factory owners, but rather the broader message of promoting CWFP technology.

Potters for Peace's independence from the financial well-being of the factories it supports reduces the organisation's capacity to leverage the capital that is created from the success of those facilities. If PfP had financial links to successful factories, the organisation could expand its influence and create more factories each year. Potters for Peace's limited resources to invest in itself, pay personnel full-time and actively market the benefits of CWFPs can be seen when contrasting the organisation's success in Nicaragua against the success of EcoFiltro in Guatemala.

EcoFiltro began production in 2008, and in the last eight years has far exceeded the market penetration of PfP, when comparing Nicaragua and Guatemala. Primarily, this is the result of EcoFiltro's sole focus on growing their market share in Guatemala, whereas PfP operates globally.

Potters for Peace has a larger global impact than EcoFiltro, working in 35 countries where the organisation has helped create over 50 CWFP factories (Rayner, 2009). Unlike EcoFiltro's market-driven approach, PfP specifically works with low-income potters to create a life-saving product and promote economic livelihood for communities, as expressed in the organisation's mission statement:

'Potters for Peace is a US-based non-profit that works in two clay-related fields: working with subsistence potters in Central America and working throughout the world to assist with the establishment of factories that produce ceramic water filters.' (Potters for Peace website)

While respecting PfP's current operational model, it is clear that the marketing structure of EcoFiltro is highly effective and would benefit future CWFP factory projects. Introducing CWFPs into schools within a community provides product exposure while also providing schoolchildren with clean water. Children, who contribute to the adoption of new technology in the household (Selwyn, 2004), are trained at school to use CWFPs and then transfer their knowledge to their parents.

9.3.1 Aspirational Products

Filtron, the largest and most successful of the Nicaraguan CWFP plants, is also the most comparable to the EcoFiltro plant. Both factories are within the same distance of the capital city, both are large foreign-owned facilities that have leveraged full mechanisation and both plants are the largest in their respective countries. But, EcoFiltro has penetrated the middle- and upper-class marketplaces in Guatemala by turning functional CWFPs into desirable objects that are part of a brand consumers want to associate with.

Creating a culture and brand that associates healthy free water with EcoFiltro products – which are highly visible in shops, hotels and restaurants in Guatemala – leverages people's desire to be affiliated with that message and spread it. Filtron is highly active within the community, but lacks the cultural movement behind its brand and, consequently, the power to attract affluent customers.

10 Conclusions

The main objective of this study – to identify the mineralogy and physical properties of clay used in Nicaraguan CWFP factories, and the effect these properties had on CWFP production – was successful. This study also investigated the current marketing and business practices of CWFP plants in Nicaragua and Guatemala, and what techniques are increasing each plants market share. A summary of conclusions from the discussion section can be found summarised below.

10.1 Physical Analysis Conclusions

- The lower clay content limit for soil used for CWFP manufacturing is between 0.5% and 3.0%, based on the results from this study. Clay that is used below this limit will produce CWFPs that do not pass PfP certification protocols.
- The upper clay content limit for soil was not determined in this study, as no samples exceeded the percentage of clay that would restrict the flow rate of water through a CWFP. Furthermore, this was not an issue at the factories visited in this study.
- The mechanical separation of clay using a hammer mill or similar device can increase the plasticity of a given clay body by breaking down aggregate clay material, which in turn liberates small clay particles that can increase the overall plasticity of the clay. This was demonstrated by the difference between Samples 1 and 5.
- Under the conditions at Filtron, CWFP that pass PfP certification can be produced using clay that contains between 16.45% and 23.5% montmorillonite.

10.2 Marketing and Business Model Conclusions

EcoFiltro and Potters for Peace invest their time and energy differently, focusing on different goals. Within their local countries, EcoFiltro has been successful at getting low, medium and high income earning Guatemalan’s to invest in their products. Potters for Peace on the other hand does not have the same success within Nicaragua, nor does the largest factory there, El Filtron.

On a global scale, Potters for Peace has had a greater impact than EcoFiltro, creating over 50 factories around the world that have reached 6 million people in need of water. Arguing based on impact, Potters for Peace has reached more people in need of water.

10.2.1 Creating Aspirational Products

The primary success, in this researcher’s opinion, of EcoFiltros market penetration in Guatemala is their investment in transforming the base CWFP into a status symbol that Guatemalans would want in their homes and business. Creating a tiered product line, rather than a one-size fits all solution, which may be viewed as a product for the “poor”, creates choice and generates aspiration for those who can not yet afford a more advanced model of the CWFP.

Shifting the appeal of a CWFP into an aspirational product generates the following positive outcomes:

- Filtering water at home in place of consuming bottled water reduces plastic use, decreases the quantity of water transported and lowers the overall carbon footprint of the user
- The drive to use CWFP is no longer based solely on need, but on social pressure by consumers and communities to “fit in”, potentially increasing the product adoption and decreasing the incidence of disease
- A broad product range may create side business that spur economic diversification for materials, artists, potters and manufacturing supplies

10.2.2 Capacity to Share and Spread technology

The Potters for Peace mandate is to work with subsistence potters to assist in the establishment of CWFP factories. They succeeded at this goal. They have created a technical model and method to teach potters around the world using a range of materials, clays of different mineralogy’s, combustible materials made from saw-dust or coffee or coconut husks to create CWFP that adhere to PfP tolerances and supply clean water to their users. There could be advantages developing a blended model between that of PfP and EcoFiltros.

Developing a training program with the global reach of PfP and the market penetration of the EcoFiltro business model would be advantageous in reaching the 780 million people around the world without access to water.

10.3 Recommendations for Future Study

The following are recommendations for future research related to questions that arose in this study but were unable to be resolved to do a lack of time or resources:

- What is the upper limit for montmorillonite composition for a clay being used to manufacture CWFP before the negative aspects of shrinkage in the final product become detrimental?
- What is the carbon footprint of a CWFP factory?
- How much carbon is offset when users switch from bottled water to filtering water at home using a CWFP?
- What is the global market share of people who do not trust the drinking water in their home/business/community, and choose to use other sources?
- What is the limiting factor preventing CWFP from mass adoption in rural areas of developing countries?

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