INVESTIGATING THE EFFECTIVENESS OF A VARIETY OF HOUSEHOLD WATER TREATMENT SYSTEMS ON MICROBIALLY CONTAMINATED WATER IN AREQUIPA, PERU 2004

By:
Amber Jaycocks
Jennifer Lappin
Robert Malies

Supervisor: Susan Murcott

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Massachusetts Institute of Technology
Department of Civil and Environmental Engineering

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1.0 MIT Agua Peru Investigation

The purpose of this experiment is to test in the laboratory household water-filtration system performance using local water resources. Performance is evaluated on thermotolerant coliform[1] (TTC) removal efficiency, turbidity reduction, flow rate, and the costs to construct and operate the filters in the Department of Arequipa, Peru.

1.1 Design Overview

The MIT research team constructed four household water filtration systems in a workspace at the Clinic of the Sociedad Misionera de San Pablo, Enace, Alto Cayma, Department of Arequipa, Peru. The filter elements were of established, commercially- available drinking-water treatment components. Wherever possible, filter systems were constructed using materials procured locally; however, due to time constraints of the project, the team brought Pozzani and Katadyn ceramic candle filters that were purchased in the United States prior to departure. All other construction materials were purchased or obtained in Peru. During the construction phase, costs and location of purchase were recorded.

The research team tested the following four filter systems for TTC, turbidity, chlorine residual and flow rate:

1) The Household Slow Sand Filter (HSSF)
2) The Pozzani Ceramic Candle Filter, Two Candles
3) The Katadyn Ceramic Candle Filter, Two Candles
4) The Table Filter (Filtro de Mesa)

The four filter systems were tested with sample waters taken from drinking water sources throughout the Department of Arequipa, Peru. TTC levels were tested pre- and post- treatment. TTC removal was evaluated using the membrane filter technique with sterile lauryl sulfate growth medium, Standard Method 9222- D.[2] The research team recorded the turbidity of the water sample pre- and post-treatment using Standard Methods 2130 B.[2] Flow rate was assessed under various conditions and due to the differing filter system constructions and mediums, flow rate methods were adjusted to accommodate the individual filter systems. Tap water was used to measure the flow in all cases.

For just the ceramic candle filters (Pozzani and Katadyn), water was filled to a level almost flush with the tops of the candles (Pozzani – 5.8 liters, Katadyn – 6.7 liters). In addition to this, all flow rates were tested with the filters being filled to the uppermost level possible (Pozzani – 21.4

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[1] Thermotolerant coliforms are a genus from the family Enterobacteriaceae and are characterized by their ability to ferment lactose at 44º C. Quantifying the presence of TTC in water is a standard set by the World Health Organization Water Quality Guidelines (www.who.int), the premier international guideline.

[2] Standard Methods for the Examination of Water and Wastewater, 20th ed. (1998)

liters, Katadyn – 21.4 liters, HSSF – 3.4 liters [above standing water level] and Table Filter – 18.4 liters).

For the Pozzani, Table Filter and HSSF flow rate tests, the volume of water that had passed through the filter was recorded at times of 1, 2 and 5 minutes after the filter had been filled. For the Katadyn, 60 and 120 minutes were used, as the flow rate was so low.

1.2 Filter Descriptions

1.2.1 Household Slow Sand Filter, HSSF

The HSSF is based on the commercially-available Davnor HSSF Filter, but employs less expensive materials and a simpler design. The main body is composed of a 20-liter High Density Polyethylene (HPDE) transparent container with a pipe protruding from the container. The slow sand filtration process treats the water. Three layers of sand sizes, fine (1mm), coarse (1-2mm), and gravel (5-6mm), are arranged to specified depths inside the container. The grain size and layout creates aquatic conditions wherein the *schmutzdecke,* a beneficial bacteriologic layer, forms at the top of the fine sand, above which approximately 5 cm of water lies; the *schmutzdecke* can retain and destroy the thermotolerant bacteria. Chlorine can destroy the *schmutzdecke*; therefore, if chlorinated water passes through the HSSF, the biologic layer will be damaged and the effectiveness of the filter reduced.

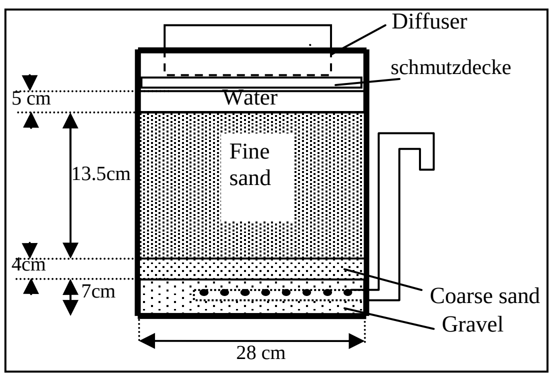

Figure 1: A schematic of the HSSF.

Figure 2: The HSSF filter built in Peru by the MIT team.

Previous MIT experiments demonstrated that the HSSF has a logarithmic reduction value (LRV) for thermotolerant bacteria removal of 2.01 (99.0%), Appendix 1.

Prior research has shown the HSSF to be capable of reducing turbidity by 87 %, Appendix 1.

In previous lab experiments the HSSF showed flow rates around 4 to 60 liters/hour.[3] The Davnor HSSF Filter (Model MS-20) is advertised to yield flow rates of 30 liters/hour.[4]

Costs of construction are variable, depending on the cost of container, pipe/tubing, etc. The commercially available Davnor HSSF costs $265 USD.[3]

1.2.2 Pozzani Ceramic Candle Filter, Two Candles

This filter is constructed using two Brazilian-made Pozzani ceramic candles; Pozzani candles come in several different sizes and for this experiment, the shorter, 3-inch Pozzani candles were used. The main body of the filter system is composed of two 20-liter HDPE transparent pails, where two Pozzani ceramic candles of 0.9 micron pore size, are positioned in the uppermost pail to allow water to exit through the ceramic candle and into the bottom HPDE pail positioned directly underneath. The treatment process is based on the physical properties of the ceramic candle; the pore size of the candle is designed so that it is large enough to allow water to flow through, and small enough to prevent most thermotolerant bacteria and colloidal solids from passing through the pores.

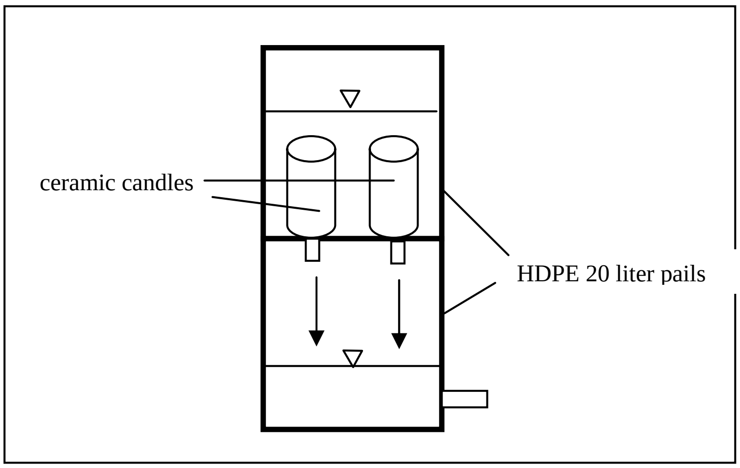

Figure 3: A schematic of the Pozzani and Katadyn filter systems.

[3] Lukacs, Heather. *From Design to Implementation: Innovative Slow Sand Filtration For Use in Developing Countries*. MIT MEng Thesis, Cambridge, MA, 2002, p59.
[4] *Water Tiger HSSF Manually Operated Water Filters.* Tiger Purification Systems, Inc. 28 Sept., 2004 < http://www.watertiger.net/davnor/HSSF_manual.html >

Figure 4: The Pozzani filter system built by the MIT team in Peru on the left.
A ceramic Pozzani candle is pictured on the right.[5]

Independent testing has determined that these filters are capable of reducing 99.99% (4 LRV) of indicator bacteria[6] and the company reports 99.8% (1.7 LRV) bacteria removal efficiency with a turbidity reduction of 98%.[7] Ceramic candles have an estimated flow rate of 1-2 liters/hour.[8]

Pozzani candles can be purchased directly from the company, located in Brazil, at a cost of around $1.50 USD per candle (large orders), not including delivery costs.[5]

Costs of filter-system construction vary, depending on the price of the two containers and the spigot as well as the cost of purchasing two Pozzani candles; the price per candle was approximately $8 USD for each filter (not including delivery costs).

The useful lifetime of a ceramic filter is determined by the initial thickness of the ceramic candle and how much the surface is worn away due to cleaning. Cleaning the candle periodically is necessary to remove accumulated solids and biofilm, which form on the outside. This helps to ensure an adequate flow rate and proper function of the filter. Repeated scrubbing eventually reduces the effectiveness of the filter by wearing down the surface, and some manufacturers such as Katadyn and Pozzani recommend replacing the filter after some specific decrease in candle diameter is observed.

According to Pozzani, the filters may be cleaned with a brush up to 100 times before replacement (depending on the quality of the source water). A measuring gauge is supplied with the unit to indicate the diameter at which replacement is required.[5]

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[5] Candle Image. 29 Sept. 2004. Pozzani Co. <http://www.pozzani.com.br/produtos/agua.asp>
[6] Brown, Joe; *Evaluation of point-of-use microfiltration for drinking water treatment in rural Bolivia*, University of London MPhil Thesis. London, UK, 2003.
[7] *Pozzani Cor and Design*. 29 Sept. 2004. Pozzani Co. <http://www.pozzani.com.br/produtos/agua.asp>
[8] Lukacs, Heather. *From Design to Implementation: Innovative Slow Sand Filtration For Use in Developing Countries*. MIT MEng Thesis, Cambridge, MA, 2002, p19.

1.2.3 Katadyn Ceramic Candle Filters, Two Candles

This filter is constructed using two Swiss-made Katadyn ceramic candles; for this experiment, the shorter Katadyn candles, the 3.5-inch, were used. Similar to the Pozzani system previously described, the Katadyn system also consists of two 20 liter HPDE pails. The upper one holds two Katadyn candles positioned to allow water to leave the container only through the ceramic candle, shown in Figure 3. The treatment process is based on the physical property of the ceramic candle; the 0.2 micron effective pore size of the candle is designed so that it is large enough to allow water to flow through, and small enough to prevent most thermotolerant bacteria and colloidal solids from passing through. Unlike the Pozzani candle, the Katadyn is impregnated with a fine silver powder that inhibits biological growth in the ceramic element.

Figure 5: A Katadyn ceramic drip candle (left). The Katadyn filter system built by the MIT team in Peru (right).

Independent studies have shown the Katadyn candle to give 99.9999% (6 LRV) bacterial removal efficiency.[9] Katadyn has been reported to reduce turbidity by 99%.[10] The Katadyn has smaller pores than the Pozzani candle (.9 microns) and is expected to have a slightly lower flow rate than the Pozzani filter system. Previous MIT research has shown that the Katadyn candle filter system has a flow rate that varies between 1-2 liters/hour.

Katadyn candles can be purchased directly from the company at a cost of $9 USD each, not including delivery costs.[11]

Cost of construction varies, depending on the price of the two containers and the spigot, as well as the cost of purchasing two Katadyn candles; the price per unit in Peru is approximately $25 USD per filter. Candles need to be replaced typically after 150,000 liters or approximately every 6 months according to the manufacturer. [12]

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[9] *Water Filters from Katadyn Global Site.* Katadyn Co. 28 Sept 2004 < http://katadyn.com>

[10] Ibid

[11] *Water Filters from Katadyn Global Site.* Katadyn Co. 28 Sept 2004 < http://katadyn.com>

[12] *Water Filters from Katadyn Global Site.* Katadyn Co. 28 Sept 2004 < http://katadyn.com>

1.2.4 Table Filter, Filtro de Mesa

The Table Filter, also known regionally as the *Filtro de Mesa*, employs both sand and ceramic candle filtration techniques. A 20-liter HDPE transparent container is initially set up in the same manner as the Pozzani and Katadyn candle filter systems. Employing the same processes used in the assemblage of the HSSF Filter, sand is sifted with a 1mm mesh sieve for grain uniformity and then arranged to a specific depth inside the container to cover the candles. A geotextile is then placed on top of the sand to decrease suspended solids and turbidity. In contrast with the HSSF, the sand in the Table Filter is not intended to be the primary microbial treatment, rather the sand serves as a "rough filter" to reduce turbidity. Consequently, the candle filter is treating water with lower quantities of fine solids and this frees more pore space for microbial removal. The result is that the sand in combination with the candles enhances flow rate and reduces the frequency of cleaning the candles.

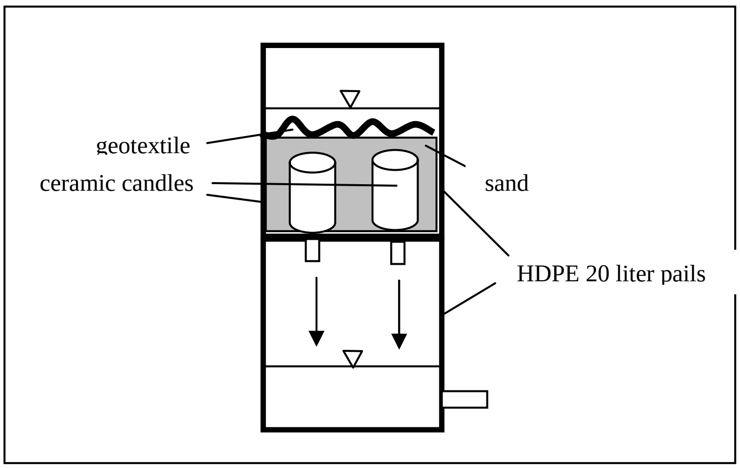


Figure 6: A schematic of Filtro de Mesa filter system.

Figure 7: The Filtro de Mesa filter system built by the MIT team in Peru.

According to Vargas and Vásquez of The Peruvian Center for Social Studies (CEPIS), bacterial and turbidity removal of the Table Filter should be the same as that of the candles inside it but with a variation longevity and flow rate.[13]
The cost of assembly is slightly greater than or equal to the Pozzani candle filter system, depending on whether sand is purchased instead of obtained locally, and if a geotextile is purchased, rather than using scrap cloth material that is available for free.

1.3 Filter Construction and Assemblage

The Pozzani ceramic candle filter system, Katadyn ceramic candle filter system, and the Filtro de Mesa filter system were all built using two 20-liter HDPE transparent pails. For these filters, two pails were stacked on each other and separated by a lid. The lid was punctured with two holes sized according to the outflow fitting of the specific candle. The holes were spaced approximately four inches apart on either side of the center of the bucket bottom. The lid was punctured by heating a hollow copper pipe and then forcefully pushing the hot pipe through the plastic.

For the Pozzani and Katadyn candle systems, the respective candles were placed upright in the upper pails. Each connection from the candle to the second pail was made water-tight and secured using two gaskets and a nut; the gaskets and nuts were supplied with the purchase of the candles from the manufacturer. The Filtro de Mesa had the same two-candle setup as the Pozzani and Katadyn systems; however, after securing the candles, the Filtro de Mesa was then filled with clean sand of 1mm diameter. A geotextile was then placed on top of the sand and held down with a polyethylene tube; shaped into a ring, the geotextile fit snuggly against the inner perimeter of the top pail.

Differing from all the other filters, the HSSF system did not employ any ceramic candles or utilize two large pails. Instead, sand (differing by the d_{60} particle sizes were 1mm, 1-2mm and 5-6mm) was sifted and separated into three layers. The three sand mediums, fine sand (1mm), coarse sand (1-2mm) and gravel (5-6mm), were washed and then placed in a single 20 L HDPE pail. Positioned on top of the large pail was a smaller diffuser bucket covered by a piece of fabric. An additional aspect that differed only in the slow sand filter was the spigot; all other filters used a toggle-type of spigot supplied and assembled during purchase while the slow sand filter just used PVC pipe.

[13] Vargas, Rojas and Vásquez, Guevara, *Filtros De Mesa, 2004.*

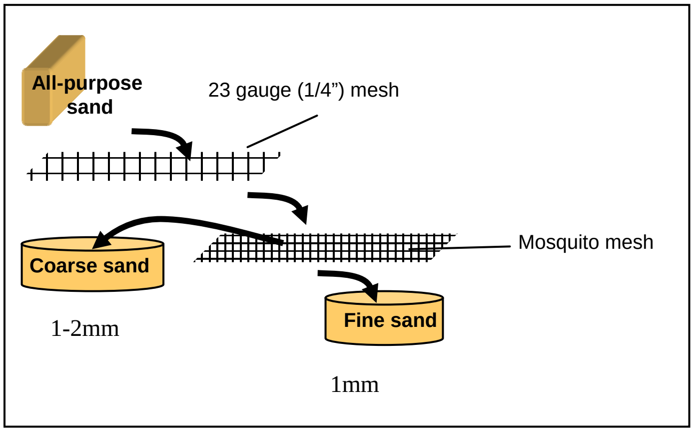


Figure 8: HSSF sand sifting process for the HSSF system fine sand and course sand.

Figure 9: Sifting (left 2 pictures) and washing sand (right two pictures) for the HSSF.
Photos taken adjacent to the Clinic of the Sociedad Misionera de San Pablo, Enace, Alto Cayma.

All systems were assembled in compliance with previously documented information and diagrams.[14]

1.4 Obtaining Materials

Material acquisition within Arequipa, Peru proved to be rather successful with the exception of specific name brand products. The 20L HDPE pails with lids were each purchased for S/20 at Loceria "Yoselin" located at Dean Valdivia No 320 in Arequipa, Peru (phone number 28 5450). The sand, gravel, PVC, silicon adhesive, hammer, and nails were all readily available at all

[14] HSSF adapted from Slow Sand Filtration for Community Water Supply in DC, a Design and Construction Manual. IRC/WHOTechnical Paper Series 11, Den Haag, Dez. 1978. Katadyn and Pozzani containment system adapted from manufacturer's drip filter system. Filtro de Mesa from the CEPIS guidelines.

hardware stores or "Ferreterías" in Arequipa. The small bucket and fabric used for the slow sand filter was supplied by the clinic in Enace. Some of the finer sand used in the slow sand filter was obtained outside of the clinic in Enace and combined with the sand purchased in Arequipa to produce the desired quantities. Both the Pozzani and Katadyn candles were purchased in the United States prior to the team's departure for Peru. CEPIS supplied the plastic rings that secured the geotextile.

1.5 Sample Water Characteristics

All water tested came directly or indirectly from the Rio Chili River. Water samples were taken from the mother canal and its extensions in La Joya and Buena Vista, home connections in La Joya and Buena Vista and directly from the Rio Chili in Alta Cayma. The canal system harnesses Rio Chili water and distributes the water throughout the surrounding areas for domestic and agricultural purposes.

Figure 10: From left to right, pictures of the canal extension in Cerrito Buena Vista, the Rio Chili, and a "pozo" (home sedimentation tank).

A preliminary MIT investigation conducted in January of 2004 in the Departamento de Arequipa indicated high levels of thermotolerant bacteria present in the water in many taps and other drinking sources. Thermotolerant bacteria is an internationally-recognized indicator of drinking water quality. Substantial quantities of TTC present often point to contamination from agricultural waste and domestic sewage.

During the January investigation, tests were carried out in Cerrito Buena Vista at the treatment plant, which showed influent CFU counts between $5x10^3$ and $2x10^5$ and effluent CFU counts around $5x10^4$. This local water treatment plant appeared to contribute little to nothing in terms of coliform reduction. On one day's testing at the plant, the effluent water actually had a higher CFU count than the influent. Also, turbidity readings were found to be very high in drinking water sources, around 80 NTU in and out of the treatment plant, and between 10 and 50 NTU in the homes. Some families already had table filters or chlorination systems given out by organizations in the past, but many were either not using them effectively or they had simply broken.

2.0 Testing Procedures

2.1 General Procedures for TTC and Turbidity

The research team filled 20 and 25 liter pails by dipping them directly into the canal while holding onto the bucket handle or by placing the buckets under the house tap or hose. The Pails were covered and transported back to the laboratory. The buckets were not sterilized between sampling as the primary purpose was not to precisely characterize the extent of TTC contamination for each of the aforementioned sources, but to analyze filter performance through TTC removal.

Source water samples were run through the filters within the range of 1 - 48 hours of source sample collection. Transportation difficulties often prevented the research team from obtaining the necessary quantity of sample water to test all four samples from one sample source. Wherever possible, the research team prioritized using the same source water for Pozzani and Katadyn filter systems, then the Filtro de Mesa system, and lastly the HSSF filter system. The experimental design chosen prioritized standardizing TTC and turbidity exposure for Pozzani and Katadyn filter systems. The candles are two different brands of the same filter technology, and the team wanted to highlight their performance in comparison to each other in their results.

Additional attempts to standardize the testing processes included pouring the water sample into an empty bucket and then back into the original bucket to mix the colloidal and suspended solid material evenly throughout the 10 to 20 liter sample. Especially large/heavy suspended solids that settled to the bottom of the mixing bucket, despite agitation, were not poured into the filters.

After this mixing procedure, the team appropriated a portion of the water into the top bucket of all four filters. Every test (after the initial test) would have approximately 1 to 8 liters of the previous sample in the top container for the Katadyn and Pozzani filter systems. This was due to the flow rate of the candles, our testing schedule/experimental design, and the construction of the filters (the base of the candle is plastic and prevents the bottom 2-cm of water in the bucket from being filtered). To account for sample mixing, sample water was taken from the top filter bucket of the Katadyn and Pozzani systems immediately after the new sample water was added. The faster flow rate of the Table Filter system and the HSSF system meant that there was never a substantial and easily accessible amount of water from the previous sample present in the top container. Therefore, pre-treatment samples were taken as the recently agitated source water samples were being poured into the top container of the filters, and not from the top bucket of the Table or HSSF. If the Table and HSSF Filter received the same source water for a test, then TTC analysis would be done on one sample and recorded as the pre-treatment sample for both the Table and HSSF.

Between tests, the bottom pails, which collect the post-treatment water from the Table, Katadyn and Pozzani filter systems were emptied by opening the spigot until water ceased to flow. Residual water remained in the bottom 2 cm of the pail below the level of the spigot. However, the team decided that it was impractical to tip the pail each time in order to fully empty the bottom container for the following reasons: first, customers who would be using the filter would not operate it as such. Second, continuous tipping and moving of the pail would disturb the sand of the Filtro de Mesa and increase the likelihood of leakage or breakage of the Pozzani and candle filter systems. Third, even with emptying of the bottom pail, it would still be unsterile, as small quantities of the previous sample would remain. Fourth, the physical construction of the

Table and HSSF filter systems created pore spaces within the sand that were always holding water from previous samples; thus, this is the reality of operation and testing for these types of filters. To dilute the effects of residual post-treatment water from previous tests, the team waited for 2 liters or more of the most recent post-treatment sample water to pass through before collecting a sample from the spigot for the Katadyn, Pozzani and Table filter systems. Upon opening the spigot, the team allowed water to discharge for five seconds before taking a sample. For the HSSF system, post-treatment water samples were taken directly from the discharge pipe immediately as flow commenced. A maximum of 5 liters per test was added to the HSSF system. Samples were taken after 2 or more liters had passed.

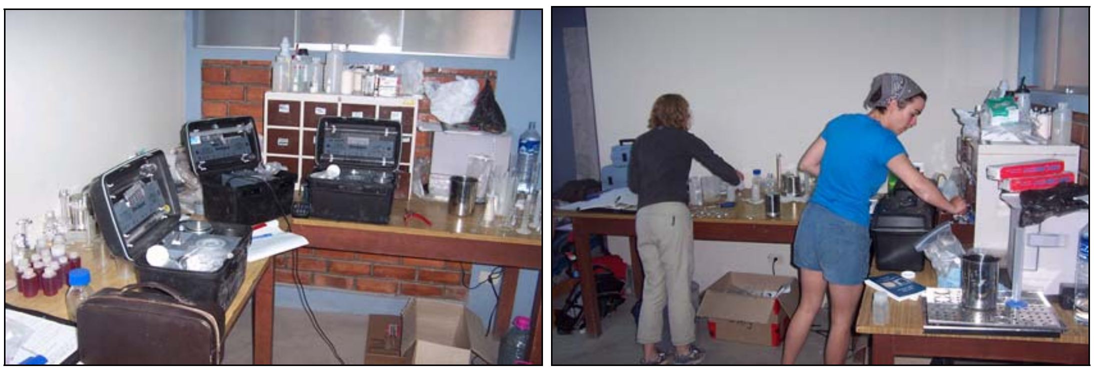


Figure 11: Pictures of the Oxfam Del Agua kits (left) and the lab in Alto Cayma.

2.1.1 TTC Design

Pre- and post-treatment samples were analyzed for TTC using the membrane filter technique with sterile lauryl sulfate growth medium, Standard Method 9222- D. The research team used lauryl sulfate that was prepared by dissolving pre-measured dry powdered lauryl sulfate medium in near boiling water. For the first two weeks of testing, plastic disposable petri dishes were used during incubation. After exhausting the disposable supply, the team used reusable metal petri dishes from the Oxfam Del Agua kits. For incubation, the team used the Single Chamber Gray Portable Incubator, 230V, owned by MIT, and the Oxfam Del Agua Incubator. The team experimented with reusing disposable plastic petri dishes, but the dishes continuously warped during the boiling sterilization process.

For HSSF and Table filter system, samples were generally analyzed within 2 hours of sampling. Standard Methods for TTC analyses call for samples to be analyzed within four hours of sampling. Pre- and post-treatment filter samples were kept at room temperature. Due to the slower flow rate of the Pozzani and Katadyn filter systems and the experimental design, post-treatment samples were generally collected and analyzed the following day.

TTC analysis was reported as the number of colony-forming units (CFUs) present in 100 mL of sample. Samples where the research team counted over 200 TTC colonies were categorized as “Too Numerous To Count” (TNTC). Standard Methods identifies the ideal range for counting colonies to be between 20-60 colonies per sample; however, the research team thought that deeming these samples TNTC above the 20-60 range was disadvantageous for interpreting results. The research team chose the cut-off at 200 CFUs, believing that the team was capable of accurate colony counting up to 200 CFUs. A Logarithmic Reduction Value (LRV) is used as a measure of the effectiveness of the filter over time. An LRV of 1 indicates a reduction by 10^1, an LRV of 2 indicates a reduction by 10^2, etc.

2.1.2 Turbidity

Turbidity is reported as Nephelometric Turbidity Units (NTU) and was tested using a HACH 2100 P turbidimeter. The turbidimeter was precalibrated and appeared to function normally for the duration of the experiment. Turbidity was measured before and after filtration. Immediately after samples were taken from the filters and prior to adding the source water into the filters, water was pipetted into the turbidimeter's small glass jar. The glass surface was then cleaned with silicon oil and a cloth, followed by readings from the turbidimeter. The water was then disposed of and the glass jar sterilized with Q-water. Further explanations of the procedure and equipment can be found in the HACH Turbidimeter manual.

2.2 Flow Rate

The flow rate is reported in liters per hour. It was measured over different periods of time and with different volumes of water, so that the change in flow rate associated with filter degradation and water input could be examined. A specified amount of water would be added to each filter. For the Pozzani, Katadyn and Filtro de Mesa filters, the top pail of the filter was removed and each candle was placed in a one liter graduated cylinder, simultaneously a stopwatch was set. After a predetermined period of time, the table filter was removed from the graduated cylinders and the amount of water that passed through the filter was recorded. For the HSSF, a graduated cylinder was placed under the PVC discharge pipe and then removed and measured at appropriate time intervals.

For the Pozzani and Katadyn candle filters, which require the most frequent cleaning, the research team chose to examine how the flow rate would vary over time without adhering to any of the advised cleaning procedures over the month of testing. Thus cleaning was only performed on one occasion (day 20). During the month of testing, the Katadyn and Pozzani filters should have been cleaned approximately 12 times throughout the month to enable the highest flow rates. The Filtro de Mesa and the HSSF should not need to be cleaned during the month of testing.

2.3 Chlorine

In the field total chlorine and pH were both measured using colorimetry methods from the Oxfam Del Agua kits. In the lab pH was measured with in a similar fashion but using pH paper. In the lab, free and total chlorine were measured with a Hach digital titrator. Similar to the turbidity measurements, both the influent and effluent chlorine and pH levels were measured.

Figure 12: Pictures of chlorine added to the water for disinfection. Liquid chlorine, occasionally used for home disinfection, pictured on the left, and powder chlorine used at the CBV water treatment plant on the right.

3.0 Field Results and Discussions

3.1 Study Site

Peru is located in western South America, bordering the South Pacific Ocean. The country lies between Chile and Ecuador with a land area of 1,285,220 square kilometers and a population of 28,409,897 (July 2003 est.). Most of the research was carried out in the Arequipa Province of Peru (Departamento de Arequipa); water was collected and information gathered in the province. About 60 miles southwest of the thriving city of Arequipa is a small agricultural village named Cerrito Buena Vista (CBV). CBV is part of the La Joya District, which lies in the Arequipa Province. Most household water supply samples were gathered in CBV. Additional samples were taken from the town of La Joya (approximately 10 miles from CBV) and Alta Cayma (5 miles outside of downtown Arequipa City)

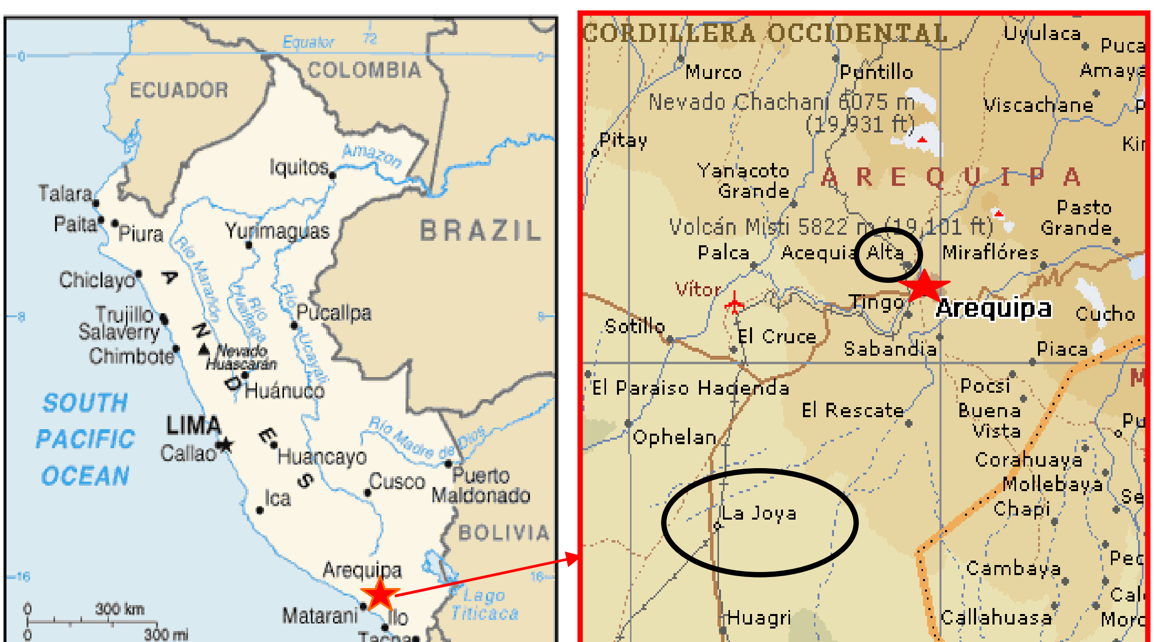


Figure 13: Maps of study location: Left map taken from the 2004 CIA online World Factbook, Peru. Right map taken from Microsoft Encarta, 2004.

3.1.1 Demographics[15]

The *Pueblo Joven* (young town) of Cerrito Buena Vista (CBV) is located approximately 75 kilometers southwest of Arequipa City in the Department of Arequipa, Peru. La Joya lies to the west of the Andes in the Peruvian coastal desert range. The pueblo is approximately 1 square-kilometer and is solely residential; the surrounding agricultural fields are located in the pueblo La Joya. CBV became an officially recognized pueblo in 1973.

Two hundred and fifty families or approximately 1,800 residents live in CBV. Of the 1,800 inhabitants, 1,400 were born and raised in CBV and approximately 400 emigrated from the Andean regions near Puno and Cuzco. The majority of the residents speak Quechua as their first language and Spanish as their second. Most families have between 2 and 8 children. There are approximately 180 elders (identified as grandparents) presently living in CBV. According to the village president, there are between 30-35 births each year and life expectancy is between 60-70 years.

Figure 14: Pictures of Cerrito Buena Vista, La Joya, Peru.

Roughly 50% of the village adult population cannot effectively read or write; 30% of CBV adults cannot write their names. Currently, there are 30 children enrolled in pre-primary school and 120 students enrolled in primary school in CBV. Of those120 children, approximately 90% continue their studies in secondary school in the neighboring town of La Joya. Very few residents have attended university, and those that did obtain higher education have not returned

[15] The MIT research team interviewed Cerrito Buena Vista President Clemente Vicente Yucra Mamani on June 23, 2004; Padre Alex Buscilli translated. The following paragraphs contain information provided by President Clemente Vicente Mamani, and information garnered from site visits and water sampling in June 2004.

to reside in CBV. For adult education, a local teacher is currently tutoring 30 women in reading and writing.

Everyone in CBV earns their living through agriculture; there are no professionals residing in CBV. Less than 15 people in CBV own lands and the remaining residents work in the fields for La Joya or CBV landowners or, to a lesser extent, graze cattle. Female field workers make approximately 13 soles a day ($3.75 USD) and males earn 20 soles a day ($5.75 USD). On average, CBV field workers seek daily employment five days a week but frequently can only find work for four of those days. The typical work day is from 7 -11 a.m. and 12 - 5 p.m., although this schedule varies. The president said that 75 families graze cattle in lieu of fieldwork and sell the milk to a nearby milk factory, but he estimates the net profit is equivalent to working in the fields.

For Pueblos Jovenes like CBV, the local government is organized as follows: CBV has a president, vice president, a general secretary, treasurer, fiscal assessor, and two vocals who are representatives for the residents. Positions carry two-year terms. Other institutions in CBV include the local health department, education and, to a lesser extent, the Catholic Church.

3.1.2 Water Resources and Uses

CBV obtains its water supply from the main canal diverted from the Rio Chili. The Rio Chili is a snowmelt-fed river running through southern Peru; the source water originates in the highland region of Arequipa Province in Vincocaya, flows between Volcanoes Misti and Chachani and cuts through Arequipa City, where it receives the waters of the Chiguata and the Yura rivers. As it flows southwesterly toward the arid agricultural region of La Joya, it is known as the Vitor River; as it flows to the Pacific Ocean, the river is referred to as the Quilca River.

In 1985 the CBV local government association with the assistance of residents installed a gravity-fed delivery system for the entire village. The system diverts Rio Chili water from the main into a side canal, where it passes through a net to remove debris; the water is then stored in two reservoirs approximately 5 square-meters in area. The storage time removes some of the turbidity through settling. With a crude dispenser that does not adjust for changes in flow rate, chlorine is added to the water supply at unknown quantities. Both MIT January 2004 and Summer 2004 teams visited the CBV treatment facility. Throughout the weeks of testing the CBV tap water (prior to any household treatment), the MIT team found insignificant to zero free chlorine, low to no levels of total chlorine, and high fecal coliform contamination. This suggests that the chlorine that is being added is not being added regularly and/or the quantity of chlorine is insufficient. The Summer 2004 MIT team did not visit the La Joya treatment plant.

Figure 15: Pictures from the treatment plant in CBV.

After the chlorine is added, water is dispensed to the houses from the reservoirs.[16] The president mentioned that all of the families have their own small reservoirs in their yards as a backup supply; during high water-usage periods, the daytime, there is not enough pressure for distribution and the water frequently ceases to flow. Families refill their reservoirs at night.

According to Mamani, every family in CBV has a connection to the distribution system. Families pay $0.75 USD per month for distribution regardless of quantity used; monies generated are used for system maintenance. The association now charges $430. USD for a new connection; however, there is no more land to build a new house in CBV. In the past two years, the association made four new connections for agricultural land-owning families, at $285 USD per connection. The president said that the land-owning families are the only people who can afford the connection. The money raised was used to replace distribution pipes.

Mamani commented that the distribution system has the advantage in that residents do not have to walk down to the canal to fetch their water; however, children and some of the elderly will occasionally drink straight from the tap, not making the distinction between delivered and household treated water.

[16] During the interview with President Mamani, the translator, Padre Alex, said there was no water treatment process aside from settling. During both site visits, M.I.T. teams confirmed that CBV added chlorine before distributing on the days they visited. It is unknown if there was a translating error, if Mamani meant there was no effective treatment, given the high contamination levels, or if he believed there really was no treatment.

The primary household water treatment technique employed in CBV is boiling. President Vicente said that hardly anyone uses chlorine at the household level. Our sampling and house visits confirmed this. There have been two household water treatment interventions in CBV in the past ten years. The local health post distributed 70 Bidon filters at a cost of $1.50 USD. The local school received 10 Bidon filters and 60 were distributed to 'high risk' residents of CBV, pregnant women and families with many young children. When asked about this filter intervention, Mamani said that some families found the Bidon too complicated and approximately 20 of the 60 families have stopped using the filter. In 2003, CEPIS, the Pan American Center for Sanitary Engineering and Environmental Sciences, distributed table filters in conjunction with a Belgian NGO. Mamani said that CEPIS did not consult the association before distributing the filters and that the distribution process was perceived as unfair. There is also some question as to how many filters were actually distributed—CEPIS said they distributed 100 but the president asserts it was less. CEPIS instructed people to continue boiling their water after filtering and to wash the sand once a month. There is no information about if the filters are still being used and if they were properly maintained in CBV. In summary, the president views prior home water-filter interventions as mostly unsuccessful. Of the approximate 60 homes visited in CBV, the MIT research team encountered one CEPIS Table Filter, and it was in active use.

3.2 Water Supplies to Households

Water supplies to households are defined as the primary site where a family obtains its drinking water within the home compound. In the majority of the samples taken, interviewers and the research team would request to take a water sample in the manner of the household's typical water collection; this would be just prior to the family's deliberate treatment regimen, (usually boiling). Sample water was taken either from the tap, or from small household storage wells called "pozos."

Boiled water samples were also collected from the household's boiled water storage container. The water sample type, pre- or post-treatment, is noted in the results below. In the interviews, every household in La Joya and the main study locale, Cerrito Buena Vista, said they performed one or more treatment regimens prior to water consumption.

Given below are a variety of CFU counts for TTC, Turbidity, pH and Free Chlorine found in household water supplies.

3.2.1 La Joya, Arequipa (population – approx. 16,000)[17]

La Joya Tap Water Quality Data

Below is data obtained from tap water samples that were collected from houses in the town of La Joya.

Table1: Tap Drinking Water Quality Characteristics (prior to additional household treatment) from samples taken in La Joya, Arequipa. June 2004.

[17] *Population estimate for age groups by province and district 2003*. Ministry of Health, Peru; 29 Sept. 2004. http://www.minsa.gob.pe/estadisticas/estadisticas/poblacion/012003DI04.htm

House Sampled	Field Tests		Laboratory Tests			
	pH	Free Chlorine [mg/L]	Turbidity NTU	Chlorine [mg/L]		TTC
				Free	Total	Colonies/100 ml
1	8.2	0	4.85	0	0	0.00E+00
2	8.2	0	4.86	--	--	8.05E+05
3	--	--	4.43	0	0	0.00E+00
4	7.4	0	5.47	--	--	1.00E+02
5	7.4	0	5.29	--	--	2.00E+02
6	8.1	0	3.89	0	0	0.00E+00
7	7.3	0	5.96	--	--	0.00E+00
8	7.6	0	4.71	0	0	3.30E+03
9	7.6	0	4.71	0	0	5.00E+03
10	7.3	0	5.07	--	--	0.00E+00
11	7.2	0	4.56	--	--	0.00E+00
12	7.4	0	4.97	--	--	0.00E+00
Average	**7.6**	**0**	**4.90**	**0**	**0**	**6.78E+04**
Variability	**0.38**	**0**	**0.53**	**0**	**0**	**232164**

Even though the average CFU count looks relatively high in the table above, it should be noted that five out of the twelve houses produced non-zero counts. These high CFU counts possibly suggest that some houses have either a bad connection or simply do not keep their cups, sinks, etc. sanitary and that the town water supply is actually clean.

The free chlorine results indicate no chlorine residual within the water. It was known that chlorine was added to the town's water supply at the treatment plant and therefore these low values indicate that the amount used is insufficient to consistently disinfect the water. The pH is between 7.9 and 8.2, which meets WHO's clean drinking water guidelines of 6.5-8.5.

La Joya Household Water Treatment Methods for Tap Water

Every interviewed household informed the team that they treated their water in some manner; 93% (14 of 15) of the families boiled their water from 2-10 minutes only one family performed dual treatment by boiling the water and then adding chlorine. Most families did not have boiled water available to sample. Below is the information for the households that were able to supply the team boiled tap water.

Table 2: Post-Household Treatment Water Quality Data from samples taken in La Joya, Arequipa. June 2004.

House Sampled	Field Tests		Laboratory Tests			
	pH	Free Chlorine [mg/L]	Turbidity NTU	Chlorine [mg/L]		TTC
				Free	Total	Colonies/100 ml
1	8.2	0	4.51	0	0	0
2	8.1	0	2.94	--	--	2

3	8.2	0	6.11	0	0	2
4	8.2	0	5.04	0	0	7
Average	**8.18**	**0**	**4.65**	**0**	**0**	**2.75**
Variability	**0.05**	**0**	**1.32**	**0**	**0**	**2.99**

The results above show a clear reduction in CFU count relative to that seen in five samples in Table 1, but the CFU level is still far above the WHO guideline where zero CFU count should be detectable in any 100mL sample.[18] The high contamination could be related to poor boiling techniques (usually insufficient time), but it is more likely that treated water is left out or kept in dirty containers, thus recontaminating the water.

La Joya is a fairly large town with easy access to products such as gas and kerosene. However, for many of the smaller villages, like Cerrito Buena Vista (see below), these products are either too expensive or too difficult to obtain. Consequently, inhabitants are more inclined to use wood for boiling their water.

3.2.2 Cerrito Buena Vista, Arequipa (population – approx. 1,800)[19]

Below is data obtained from water samples collected from houses in the town of Cerrito Buena Vista (CBV).

Table 3: Tap-Drinking Water Quality Characteristics (prior to additional household treatment) from samples taken in CBV, Arequipa. June 2004.

House Sampled	Field Tests		Laboratory Tests			
	pH	Free Chlorine [mg/L]	Turbidity NTU	Chlorine [mg/L]		TTC
				Free	Total	Colonies/100 ml
1	7.2	0	9.2	0	0	0.00E+00
2	8.2	0	2.91	--	--	2.00E+02

[18] *Drinking Water Quality Homepage from Water, Sanitation and Health Department.* 29 Sept. 2004. World Health Organization. <http://www.who.int>

[19] Approximate estimate obtained from CBV President, June 2004.

3	7.3	0	9.22	--	--	8.00E+02
4	7.1	0	6.36	--	--	3.05E+04
5	7.4	0	6.46	--	--	1.13E+04
6	7.4	0	7.56	0	0	8.75E+03
7	7.3	0	7.81	0	0	5.63E+04
8	7.2	0	3.09	--	--	1.20E+04
9	8.2	0	3.08	0	0	1.00E+02
10	7.4	0	5.59	--	--	1.21E+04
11	7.4	0	5.59	--	--	1.53E+04
12	7.4	0	11.8	0	0	1.31E+04
Average	**7.46**	**0**	**6.56**	**0**	**0**	1.34E+04
Variability	**0.36**	**0**	**2.75**	**0**	**0**	1.61E+04

Table 4: Post-Household Treatment Water Quality Data from samples taken in CBV, Arequipa. June 2004.

House Sampled	**Field Tests**		**Laboratory Tests**			
	pH	**Free Chlorine [mg/L]**	**Turbidity NTU**	**Chlorine [mg/L]**		**TTC**
				Free	**Total**	**Colonies/100 ml**
1	8.2	0	5.3	--	--	0.00E+00
2	7.4	0	5.51	0	0	1.70E+03
3	8.2	0	9.39	0	0	0.00E+00
4	7.3	0	7.89	--	--	3.00E+04
Average	**7.77**	**0**	**7.03**	**0**	**0**	**7.93E+03**
Variability	**0.49**	**0**	**1.97**	**0**	**0**	**1.47E+04**

The average CFU count for Cerrito Buena Vista was not as high as that of La Joya, but unlike La Joya the high values found in CBV were more consistent throughout the houses visited. The turbidity was higher in CBV, while the pH and free chlorine levels suggest that insufficient disinfection, 0 mg/liter of free chlorine, occurs at the town's treatment plant. During a visit to the water treatment plant in CBV, the London School of Tropical Medicine and the MIT research teams were told by treatment plant workmen that the dosage of chlorine was independent of the flow rate. This was confirmed by visual observation.

3.2.3 Raw Water Sources

In order to carry out the lab tests on the filters it was necessary to have the ability to draw bacteriologically-contaminated water from a convenient and plentiful location with contamination similar to that, which was found in the houses and used by the families living in them.

Table 5 displays data from a number of sources whose contamination levels closely resembled those in houses. The sources in the table below were used as the raw water in testing the performance of the filter systems.

Table 5: Raw Water Quality Characteristics from samples taken in CBV, Alto Cayma, and Arequipa City, Arequipa. June and July 2004.

	Location	Average Turbidity (NTU)	Average CFU /100ml	Average Free Chlorine (mg/liter)
1	Canal, Cerrito Buena Vista	15.19	1.3×10^3	0
2	Rio Chili, Arequipa	4.76	1.25×10^3	0
3	Canal, Alta Cayma (near clinic)	4.26	7.27×10^3	0

All of the above values fall within the same order of magnitude as the results obtained from Cerrito Buena Vista; therefore, results from this laboratory experiment could be extrapolated to evaluate the potential for various home water filtration interventions in CBV. It was also important that no free chlorine was present, as this could affect a sample of contaminated source water over time.

4.0 Filter Results and Discussions

Contaminated water, usually from one of the three sources listed in table 5 or of equal contamination levels, was fed into each of the four filters over a period of 27 days. For each day of testing, influent and effluent water was analyzed for turbidity and CFU removal for all four filters. Flow rate tests were also performed periodically. The date of the test, origin of the water, volume fed through the filter and any additional comments were also recorded, and can be seen in Appendix 2.

4.1 Household Slow Sand Filter, HSSF

The HSSF is a biological filter with a ripening period of several weeks. Therefore, it was expected that initial CFU removal would be poor but would improve over the course of a week or two as the *schmutzdecke* layer grew. After a period of use the filter was expected to become so full of particulates from the contaminated water that the efficacy would begin to fall. At this point flow rate would also be expected to be lower but turbidity removal should be more or less constant.

4.1.1 TTC Removal Efficacy

In the TTC tests where more than one dilution per sample was performed, an average of all counts within the required range (20 – 200), were used for that day's value.

The influent and effluent CFU counts for each day are shown below. Where there is no bar the CFU count was zero. The source water was obtained from the following locations: a family home in CBV (day 1), the canal in CBV (days 8, 9, 13, 14, 15), the Rio Chili (days 12, 16, 19), and the canal in Cayma (days 20-27).

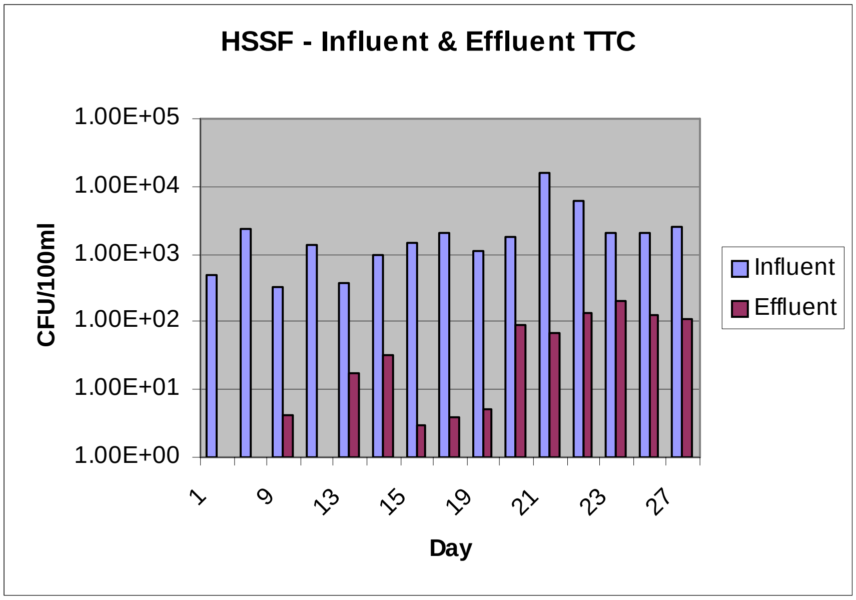


Figure 16: HSSF TTC Presence in Influent and Effluent of the Household Slow Sand Filter, June and July 2004. Based upon "Total Range" (0-200 CFU/100mL) data set.

The results of LRV over the 27 days are presented below.

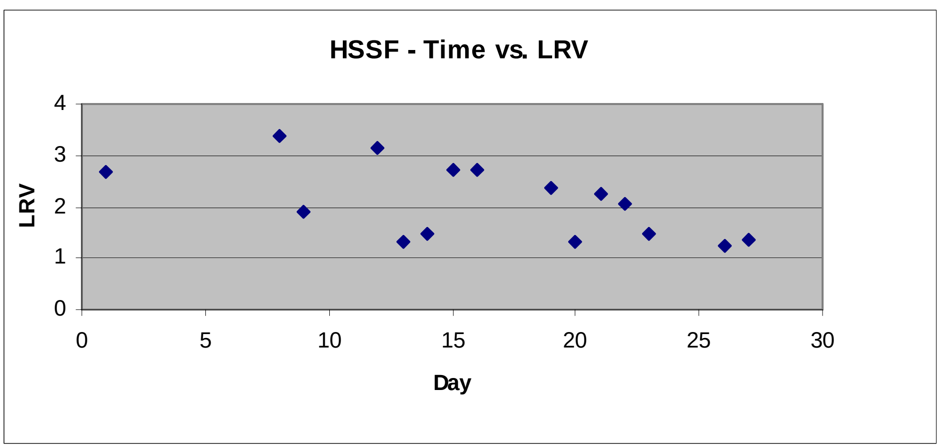


Figure 17: Logarithmic Reduction of TTC in HSSF effluent expressed temporally. June and July 2004. Water samples from Arequipa. Based upon "Total Range" (0-200 CFU/100mL) data set.

The influent contamination varied between 10^2 and 10^4 CFU/100ml and the effluent is between 0 and 10^2 CFU/100ml.

It appears that the filter performed best at the beginning of the study where multiple zero values are seen. On the first day, the filter's influent was tap water, followed by the input of contaminated influent in the subsequent days. The initial loading of clean influent delayed the appearance of TTC contaminated effluent until approximately the fourth day. However, due to the filter initially being filled with tap water (used during the construction) it wasn't until the 3rd or 4th day of tests that the influent dirty water was actually coming out the other end. Due to the different influent waters mixing within the filter it is not clear exactly when a given days influent water emerged as effluent. Despite this a day-to-day comparison of influent vs. effluent is given below to give an idea of how the performance varied during the study.

For the majority of the study the LRV is between 1.2 - 3. From figure 17, it can be seen that the effectiveness of the filter decreases with time. This is likely due to the clogging of the filter by particulates as more contaminated water was added. There appears to be a rise in quality during the first week (between days 1 and 8) but since both the effluent CFU values for these days were zero it is impossible to tell the actual improvement in quality. Note that for calculation purposes all zero values were entered as 1, thus explaining the difference between LRV for days 1 and 8.

Even though there is a general decrease in LRV over time, the variability of the results indicates that there are other factors affecting the efficacy of the HSSF.

The general decline seen in bacterial removal might be due to increasing dirtiness of the HSSF. By performing a simple cleaning process, this problem could be remedied. This would reduce the effectiveness of the filter for a short time during which the *schmutzdecke* layer would grow back. The dips are not one-offs and thus it is unlikely that they can be solely attributed to experimental error.

4.1.2 Turbidity

The influent and effluent turbidity values are shown below.

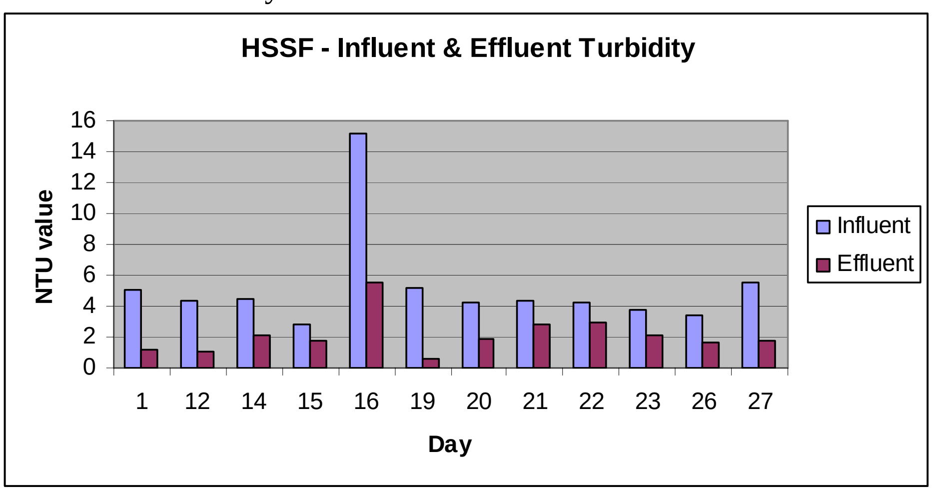


Figure 18: HSSF Turbidity Presence in Influent and Effluent of the Household Slow Sand Filter, June and July 2004. Source water from the Department of Arequipa.

The removal of turbidity by the filter was measured using % reduction. The results are shown below.

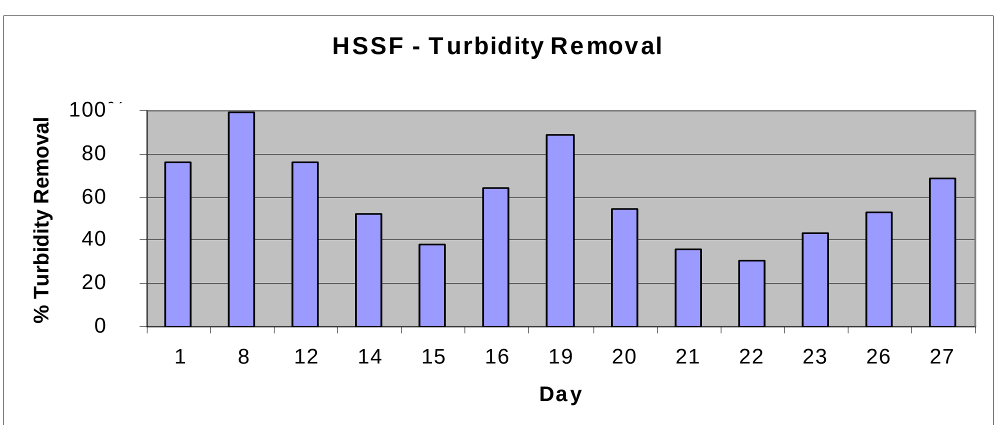


Figure 19: Percent Reduction of Turbidity in HSSF effluent expressed temporally. June and July 2004. Water samples from Arequipa.

The average % removal of turbidity is 60%.

4.1.3 Flow Rate

The flow rate of the HSSF was tested on two separate occasions, the first day using unchlorinated tap water (so as not to destroy the biological life inside the filter) and the second using water from the irrigation canal in Cerrito Buena Vista. Water was added until level with the top of the lower, 20-liter bucket (a total of 3.4 liters added to the standing water already inside).

The volume of water that flowed out after each specified time was converted to an averaged flow rate value (total volume/total time). Below are the flow rates for days 1 and 15. On day 1, zero liters had passed through the filter and by day 15, fifty-two liters passed through.

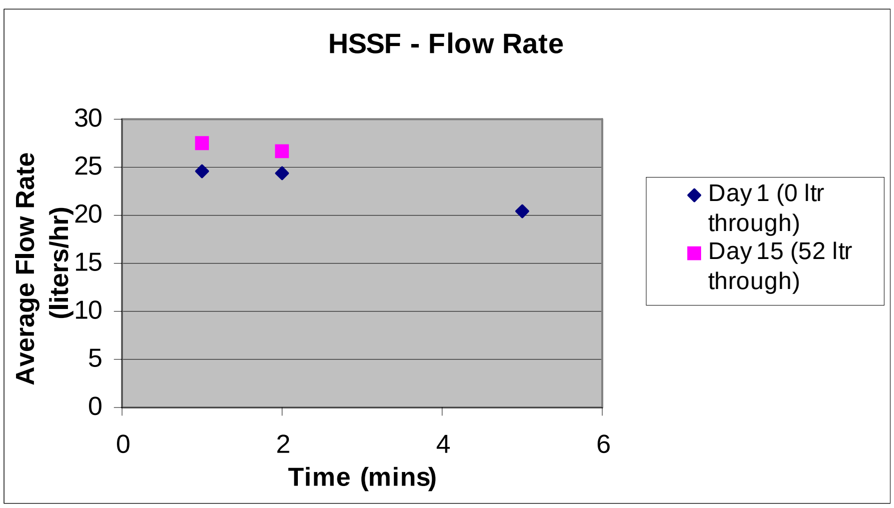


Figure 20: HSSF Flow Rate Expressed Temporally. June and July, 2004.

For both days 1 and 15, the flow rates were reduced over time, which is explained by head pressure reduction as a result of decreasing water levels. The flow rate is higher on day 15, which is surprising for two reasons. First, the flow is expected to decline over time as the filter becomes increasingly dirty and clogged, and secondly because the water used on day 15 came from an irrigation canal and was thus extremely dirty. However the values are so close that it should be concluded that the flow rate merely stays constant both over time and with different influent water within this 15 day time interval.

4.2 Ceramic Candle Filters, Pozzani and Katadyn

Both Pozzani and Katadyn ceramic candle filters have excellent reputations for microbial removal. It was expected that these two filter systems would perform the best in regards to TTC removal. However, they are more expensive and more difficult to obtain in the developing world. Additionally, the ceramic candles can be broken easily.

4.2.1 TTC Removal Efficacy

The influent and effluent CFU counts for each day are shown below. Where there is no bar the CFU count was zero.

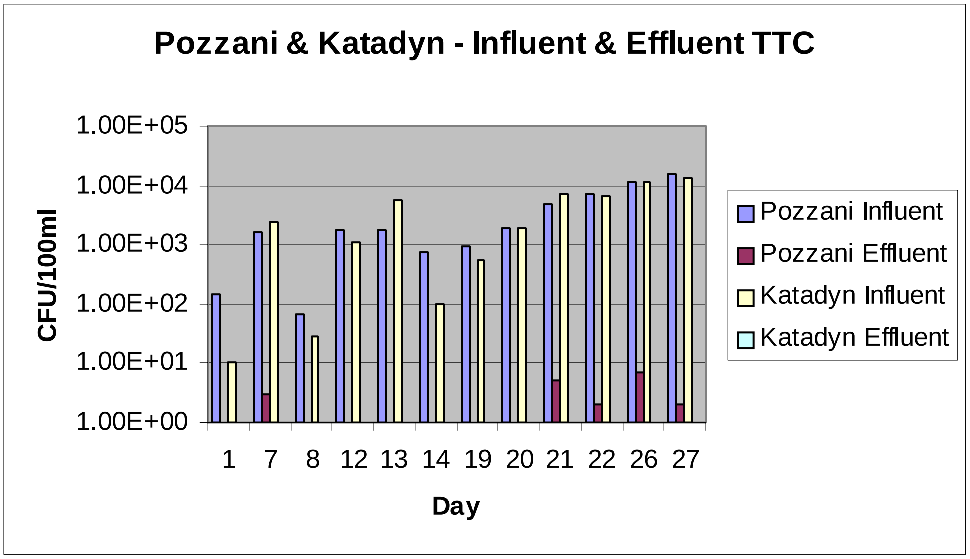


Figure 21: Pozzani and Katadyn TTC Presence in Influent and Effluent of the ceramic candle filter systems, June and July 2004. Source water from the Department of Arequipa. Based upon “Total Range” (0-200 CFU/100mL) data set.

Both filters clearly function very effectively especially the Katadyn, where a positive CFU TTC effluent result was never seen. The Pozzani, a cheaper model, still performs well, with all effluent results below 10 CFU/100ml. It should be noted that the MIT research team suspects the TTC presence in the Pozzani effluent during days 7, 21, 22, 26, and 27 was a result of contamination. We are unsure how the bottom container (storing the effluent) became contaminated. It could have been a result of emptying the water and debris in the top container. This was done only once because there appeared to be excessive amounts of debris from the turbid water. This water from the top pail was in contact with bottom of the ceramic candle (the debris could not pass through the ceramic layer and could only leave the top pail if it is physically removed). Once the bottom pail became contaminated, it is unknown how long it would have taken for the problem to correct itself. After the appearance of positive TTC levels in the Pozzani effluent on day 7, the team emptied the contents of the lower bucket containing the Pozzani effluent, and rinsed the bucket with boiled water. The negative results from day 8 support the hypothesis that contamination resulted from filter operation or construction rather than a defect in the Pozzani ceramic candle. The team did not clean out the bottom bucket for the next set of positive TTC results from Pozzani during days 21, 22, 26 and 27. Also, it should be noted that the raw water used in these tests had levels of contamination approximately between 10^3 and 10^4 CFUs of TTC per 100 mL almost 1 log higher than previous days. The Pozzani TTC removal should be closer to 99% removal, as reported by the manufacturer's statistics. If the product happened to be defective, more frequent positive results would be expected. Perhaps the Pozzani candles are overwhelmed by contamination in the 10^3 to 10^4 range. Also, it would be anticipated that the problem would not have been resolved by the corrective action of rinsing the bottom bucket on day 7.

Below are variations in LRV over time.

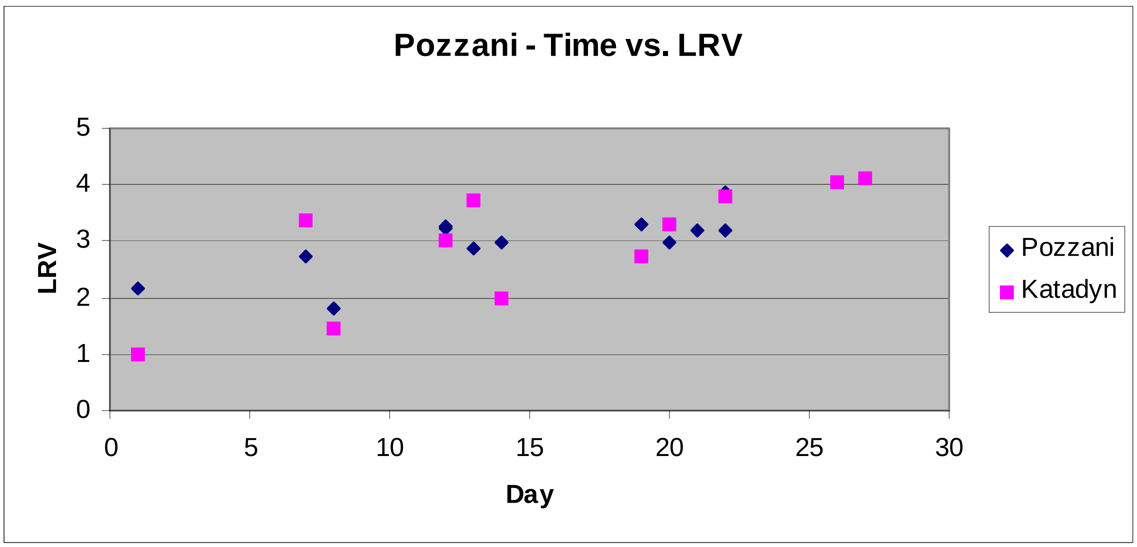


Figure 22: Logarithmic Reduction of TTC in Pozzani and Katadyn effluent expressed temporally. June and July 2004. Water samples from Arequipa. Based upon "Total Range" (0-200 CFU/100mL) data set.

The results for the Pozzani are of interest since there are some non-zero CFU values in the effluent samples. The graph shows a reasonably consistent LRV of around 3 with some inconsistencies that might either be due to experimental error or to the candle's inability to handle such a heavy load of bacterial contamination.

The results for the Katadyn as presented above are very useful. Since every effluent CFU count was zero the variation in LRV becomes solely a function of the contamination level of the influent water. Influent water with TTC contamination up to 10^4 CFU/100ml can be confidently passed through the Katadyn filter for at least one month and still give zero CFU/100ml in the effluent. Due to the similar yet higher quality of the Katadyn candle it appears that with more highly contaminated influent a reasonably constant LRV, of around 4, will be seen. Both candles were cleaned on day 20 and the team speculates this contributed to the slight rise in LRV in the Pozzani after day 20.

4.2.2 Turbidity

The % removal of turbidity is shown below for both the Pozzani and Katadyn filters.

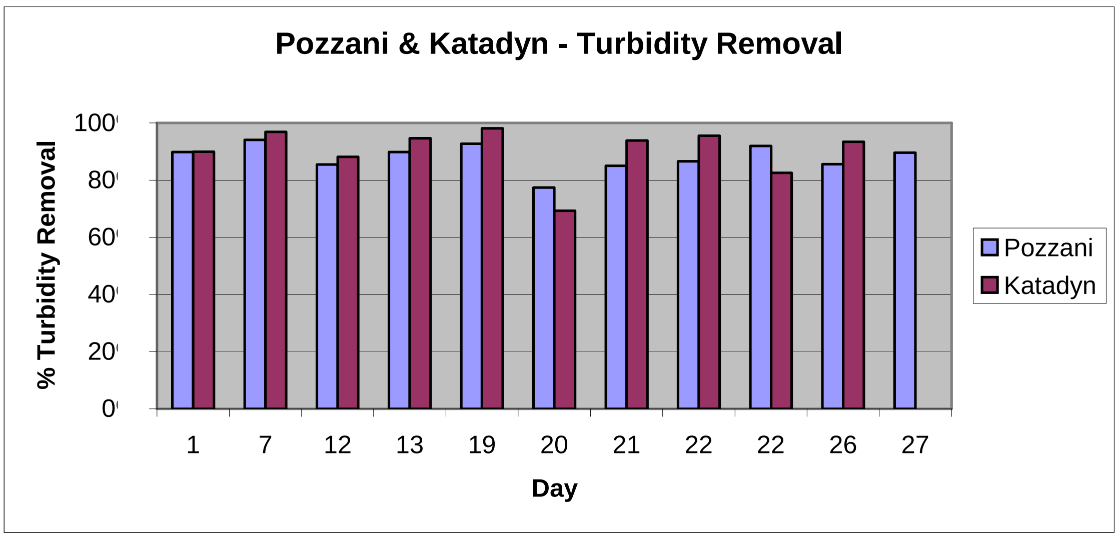


Figure 23: Percent Reduction of Turbidity in Katadyn and Pozzani effluent expressed temporally. June and July 2004. Water samples from Arequipa.

Pozzani's average % turbidity removal is 86%.
Katadyn's average % turbidity removal is 90%.

Again, the quality of both the ceramic filters is shown by the consistently high percent removal of turbidity. The value is higher for the Katadyn, as expected, but both candles show a lower removal than expected.

The dip seen at day 20 for both the Pozzani and Katadyn is almost certainly due to the cleaning that took place before the test. Cleaning unclogged pores and thus allowed slightly more particulates to pass through the candle. Cleaning may also break up the particles into smaller sizes that are able to fit through the ceramic pore spaces. This same phenomenon can be seen at the start of the study for the Pozzani when the candle would have been in a similar state.

4.2.3 Flow Rate

The flow rates of both the Pozzani and the Katadyn filter systems (comprised of two candles per system) were tested three times, on day 1 with tap water, on day 15 with canal water and then again on day 20 with tap water after having just been cleaned. On both trials the upper bucket was filled to the top (a volume of 21.4 liters).

Below is the average flow rate data for each filter and day.

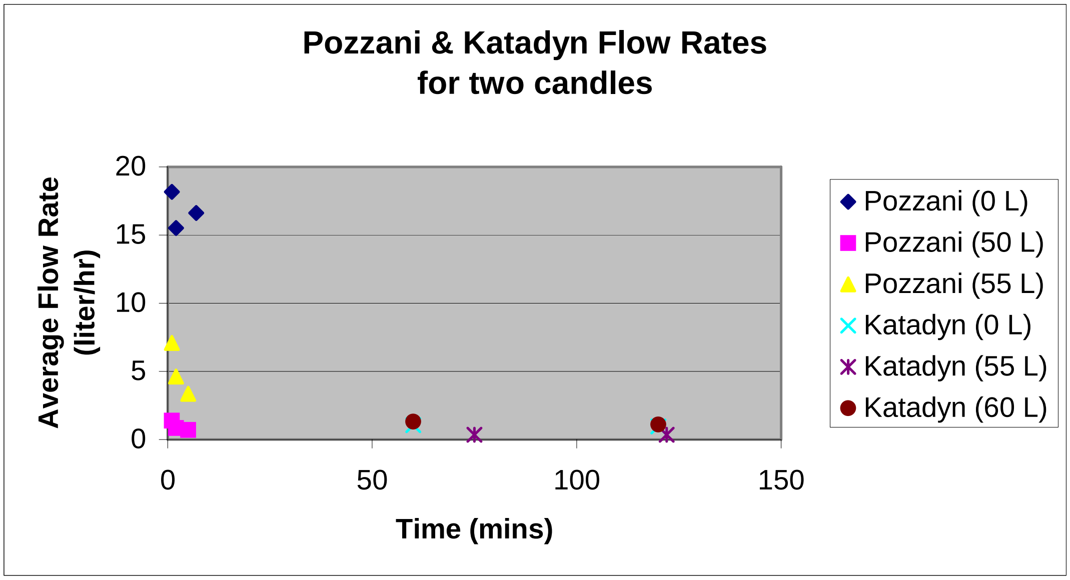


Figure 24: Katadyn and Pozzani Flow Rate Expressed Temporally. June and July, 2004.

The Katadyn filter system's flow rate was less than the Pozzani system (by around a factor of 10). The lower flow rate can be attributed to the smaller pore sizes within the ceramic, which allow more bacteria to be trapped and thus provide a superior micro-organic removal efficacy.

Excluding the Pozzani result from day 1, all tests show a reduction in flow rate over time, this is expected from the reduction in head pressure as the water level drops.

Both candles also display a large reduction of flow rate on day 15 (not shown in Figure 24). This reduction is likely attributed to the clogging of the candles over time, as well as, increasingly dirty canal water used for that day's testing. As stated in the experimental design, the research team intentionally chose not to regularly clean the filters after first exhibiting decreases in flow rates. The candles were cleaned on day 20. A ceramic candle filter will function most effectively when new. Over time the pores become filled with organic matter, which not only causes the bacterial removal to decrease but it will also reduce the flow rate.

Between days 1 and 15 the reduction in flow rate was more severe for the Pozzani than for the Katadyn. The Pozzani's flow rate dropped by a factor of 13 (18.2 to 1.4 liters/hr) whereas the Katadyn only dropped by a factor of 2.9 (1.06 to 0.36 liters/hr).

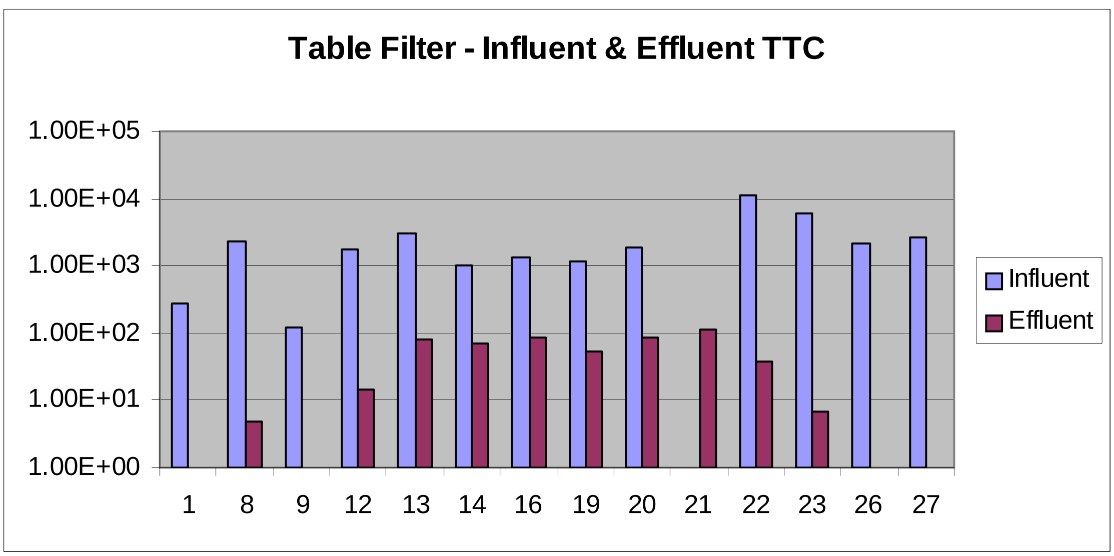
The flow rate improved from day 20 onward, as was expected, following the cleaning. It is surprising that the flow rate for the Katadyn actually surpassed its initial value following cleaning. This increase may be due to the fact that the candle was not entirely saturated when initially installed in the filter and subsequently tested.

4.3 Filtro de Mesa, Table Filter

Since, the table filter was composed of Pozzani candles it was expected to act more or less equally to that of the Pozzani filter system. The addition of sand and geotextile is expected to have some effects on flow, turbidity removal and microbial removal.

4.3.1 TTC Removal Efficacy

The influent and effluent CFU counts for each day are shown below. Where there is no bar the CFU count was zero.



[

Figure 25: Table Filter TTC Presence in Influent and Effluent. June and July 2004. Source water from rivers and canals in the Department of Arequipa. Based upon "Total Range" (0-200 CFU/100mL) data set.

All influent results are between 0 and 1.57×10^4 CFU/100ml.
All effluent results are between 0 and 10^2 CFU/100ml.

Below is the plot of LRV over time.

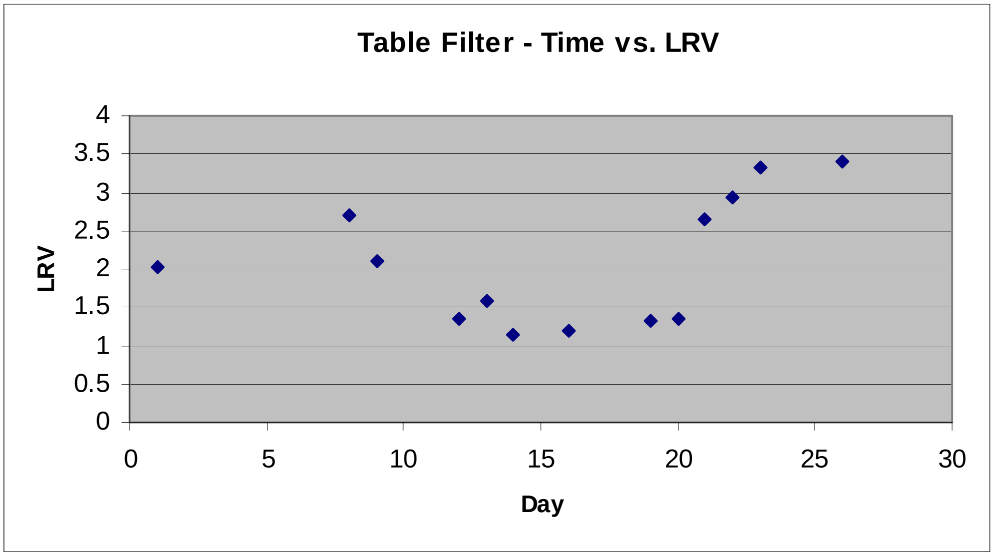


Figure 26: Logarithmic Reduction of TTC in the Table Filter Effluent expressed temporally. June and July 2004. Water samples from Arequipa. Based upon "Total Range" (0-200 CFU/100mL) data set.

A definite decrease in microbial removal can be seen up to day 20. This decrease could be attributed to the dirt and organic matter slowly forming on the geotextile and sand as more contaminated water passed through the filter. On day 22, tap water was fed into the filter and contaminated water came out thus producing a negative LRV and demonstrating that the filter itself was contaminated. After this 'flushing out' the efficacy improves again to around 3.

4.3.2 Turbidity

The % removal of turbidity for the table filter is shown below.

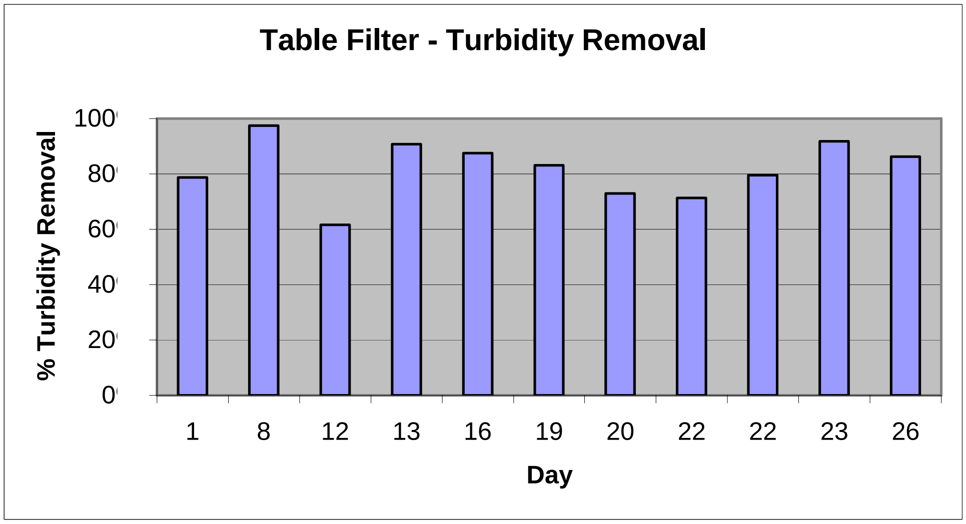


Figure 27: Percent Reduction of Turbidity in Table Filter Effluent expressed temporally. June and July 2004. Water samples from Arequipa.

The average % removal is 80%, which is worse than the Pozzani filter system without the sand and geotextile (86%). The values here are also a lot less consistent than for the Pozzani filter system alone. Both of these results are surprising as one of the main purposes of the sand and geotextile is to remove turbidity.

4.3.3 Flow rate

The table filter's flow rate was tested on two separate days using tap water and then canal water.

The results are provided below.

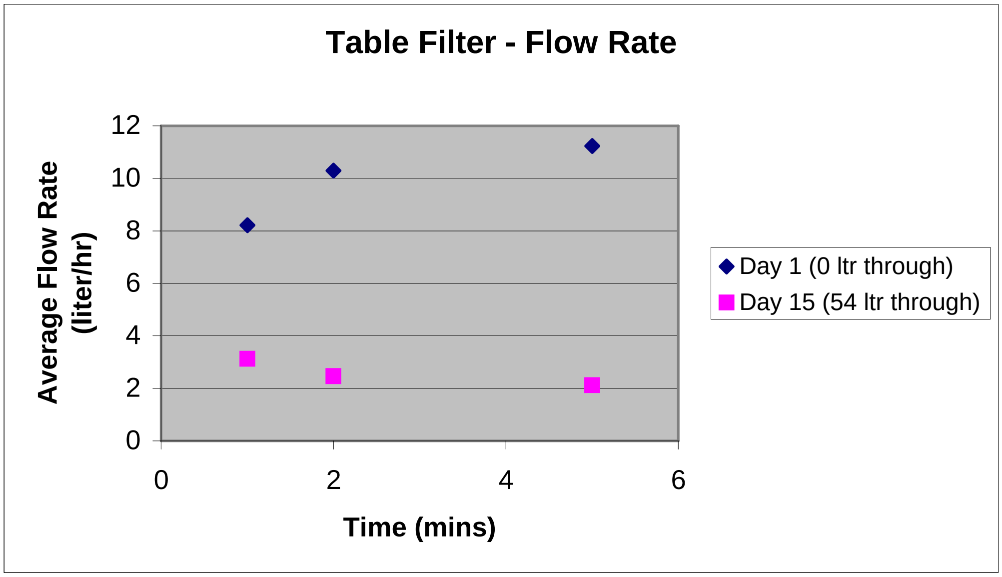


Figure 28: Table Filter Flow Rate Expressed Temporally. June and July, 2004.

The flow rate indicated above is less than that of the Pozzani at the beginning (8.2 against 18.2 liters/hr), but when comparing days 1 and 15 the reduction is substantially less for the table filter; it shows a 2.6 reduction factor (8.2 to 3.1 liters/hr) compared to a factor of 13 (18.2 to 1.4 liters/hr) seen in the Pozzani filter.

These results suggest that the only advantage of the table filter is an increased flow rate due to the geotextile and sand, over short time periods.

4.4 Filter System Comparison

The filter systems will be compared utilizing four different parameters: TTC removal, turbidity removal, flow rate, and cost of filter system components.

4.4.1 TTC

Below the logarithmic reduction value results for each filter corresponding to the testing days are displayed.

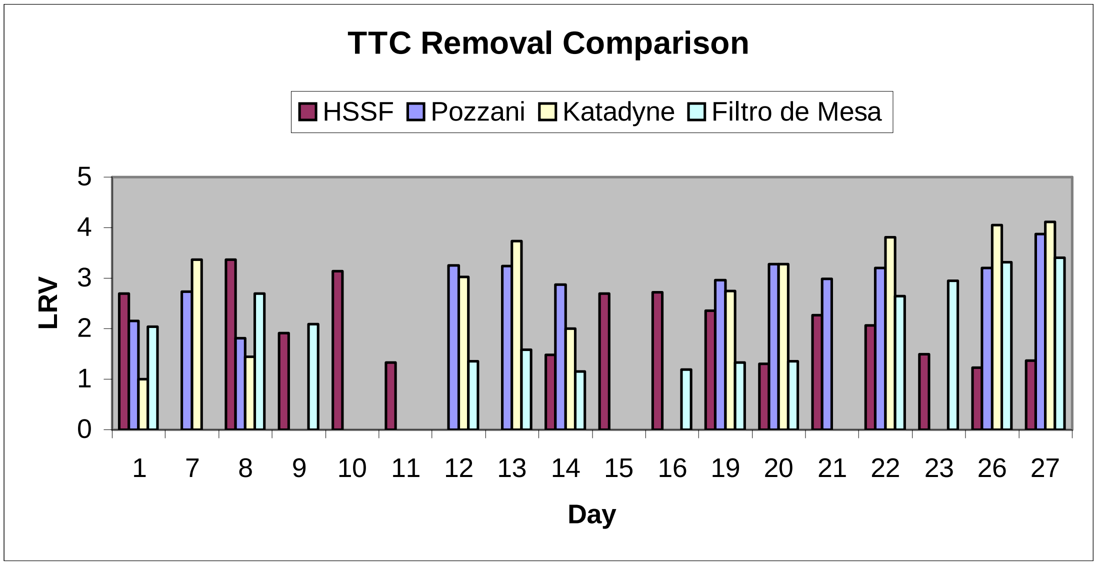


Figure 29: TTC comparison for the four filter systems using LRV calculations; based upon "Total Range" (0-200/100mL) data set.

The Katadyn filter system displays the highest LRV among the four systems. However, it is not consistent from day to day. The HSSF LRV values for the first few days are most likely erroneous and relatively high due to the accidental rinsing with tap water that contained chlorine residual. This chlorine was probably killing the bacteria thereby creating a higher LRV than from pure HSSF filter removal. The difference between the LRV for the Filtro de Mesa and the Pozzani is interesting since the Filtro de Mesa employs the use of Pozzani ceramic candles in combination with other filtration components. Comparing the Pozzani and Filtro de Mesa systems, it appears that the sand and geotextile only contribute to the effectiveness of reduction of microbial contaminants. The LRV for the table filter starts around 2 and then drops to 1. On the other hand, the Pozzani had a more consistent LRV and is also higher (between 2 and 3). By examining the trends, it appears that the Pozzani filter system has the most consistent and high LRV for TTC over this time period. (The reader is referred to Coulbert, Brittany. 2004. "Comparison of 'Table Filters' (Filtros de Mesa) and the Safe Water System in Peru." Master of Engineering Thesis. Massachusetts Institute of Technology, Civil and Environmental Engineering Department. Cambridge, Massachusetts)

Below the average LRV for TTC is displayed. This figure shows that the Pozzani filter system does have the highest LRV for TTC, followed closely by the more expensive Katadyn system.

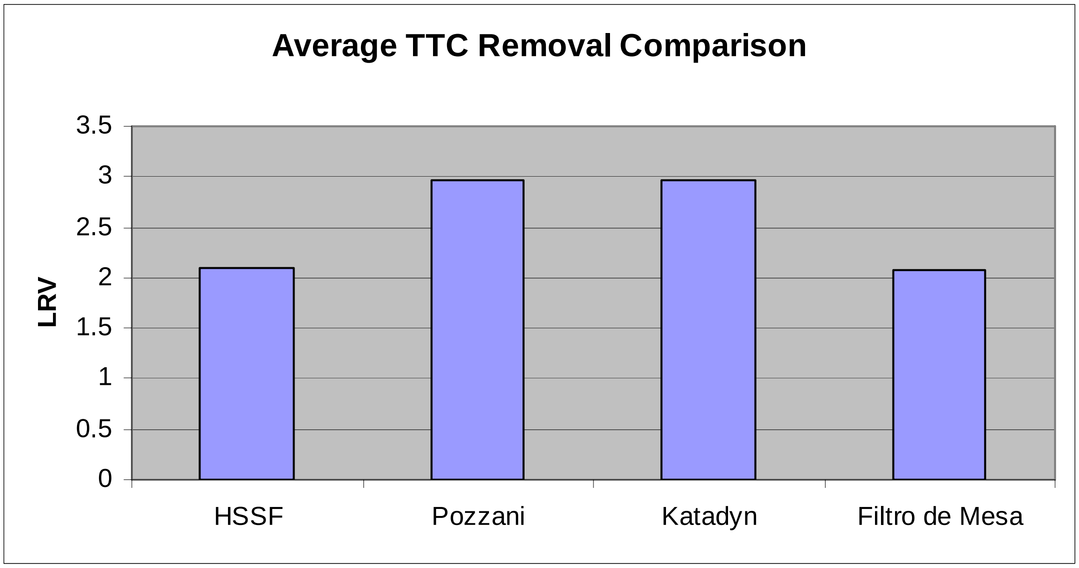


Figure 30: Average TTC removal for the four filter systems; based upon "Total Range" (0-200/100mL) data set.

4.4.2 Turbidity

Below is the percent removal of solids (measured as turbidity) comparison of the four filters. The results for each filter correspond to the respective testing days.

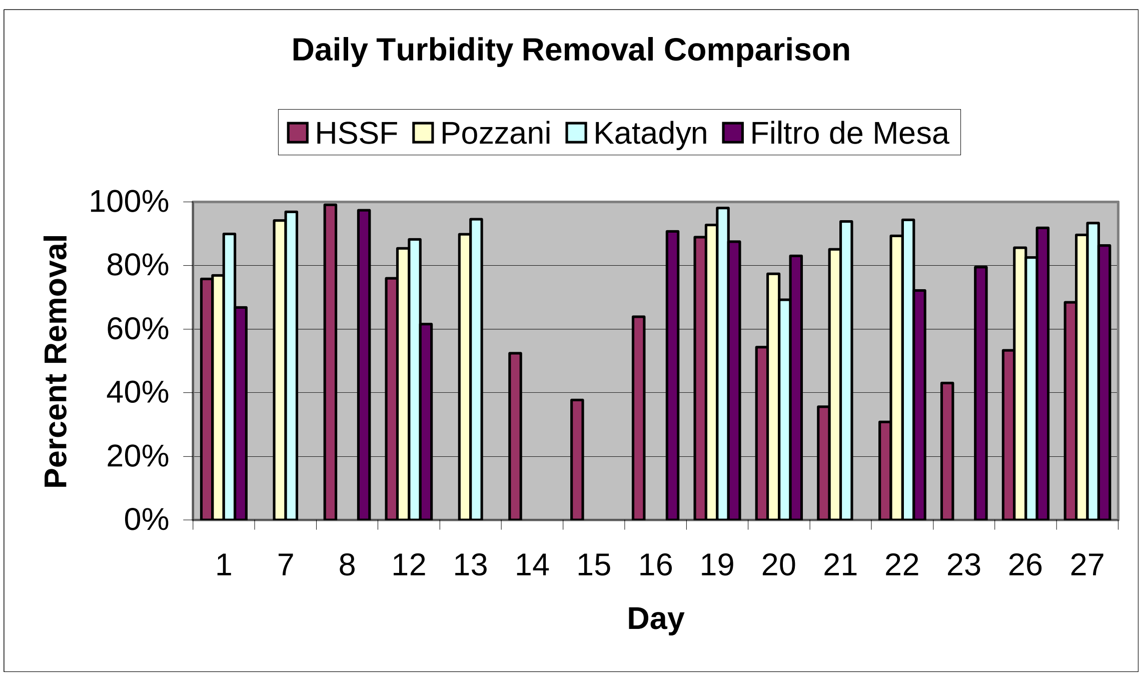


Figure 31: Comparison of the percent turbidity removals for each filter system.

The most noise is seen from the two filter systems that employ the use of sand: the HSSF and the Filtro de Mesa. The ceramic candle systems, Katadyn and Pozzani, appear to remove turbidity with relatively high rates, rarely dropping below the 80th percentile.

In figure 31, the average percent turbidity removals are displayed. The Katadyn system seems to maximize removal at 91%. This system is closely followed by the Pozzani system at 86% and the Filtro de Mesa at 82%. The HSSF system removed in the lowest percentile at 60%.

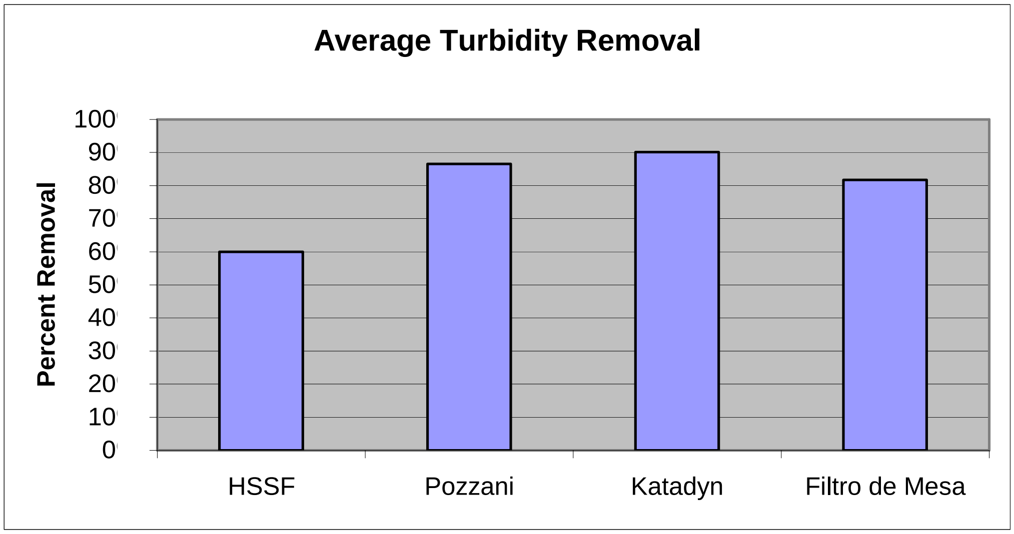


Figure 32: Average turbidity removals for each filter system.

4.4.3 Flow rate

Below the flow rates for each filter are presented. Flow rate measurements were taken on two to three occasions. The first measurement was taken when the filter was new, with the initial first liter of water filtering through the system. The additional measurements were taken after 50-60 liters of water was filtered through the system.

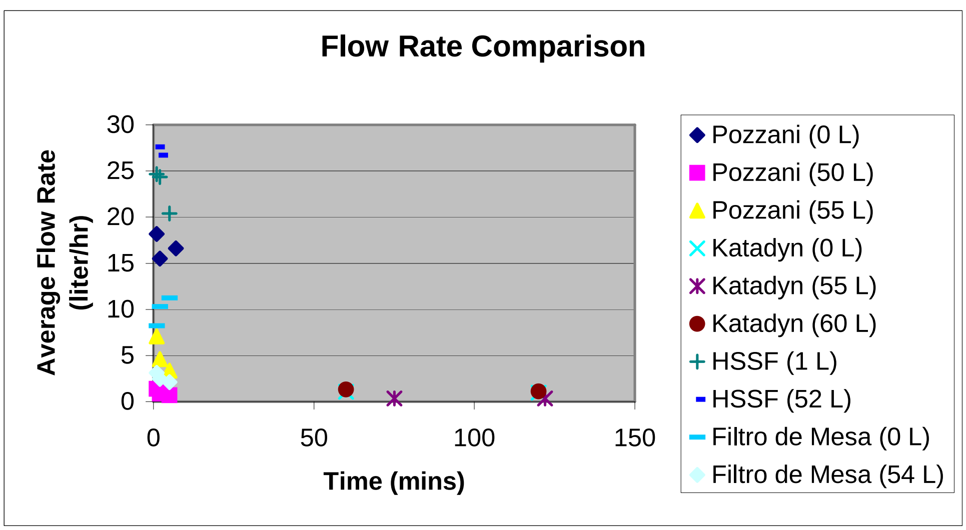


Figure 33: Flow rate comparison of the filter systems at different times and with different amounts of water.

From figure 32, it can be seen that there are a few outlying points where the flow rate was much slower than the other points. These points all correspond to measurements taken from the Katadyn filtration system. Not only is the flow rate for the Katadyn system relatively low, but in order to obtain an adequate amount of water to determine the measurement, the team had to wait significantly longer for water to pass through the filter.   Below, figures 33 and 34 display the flow rate results omitting the Katadyn data points.

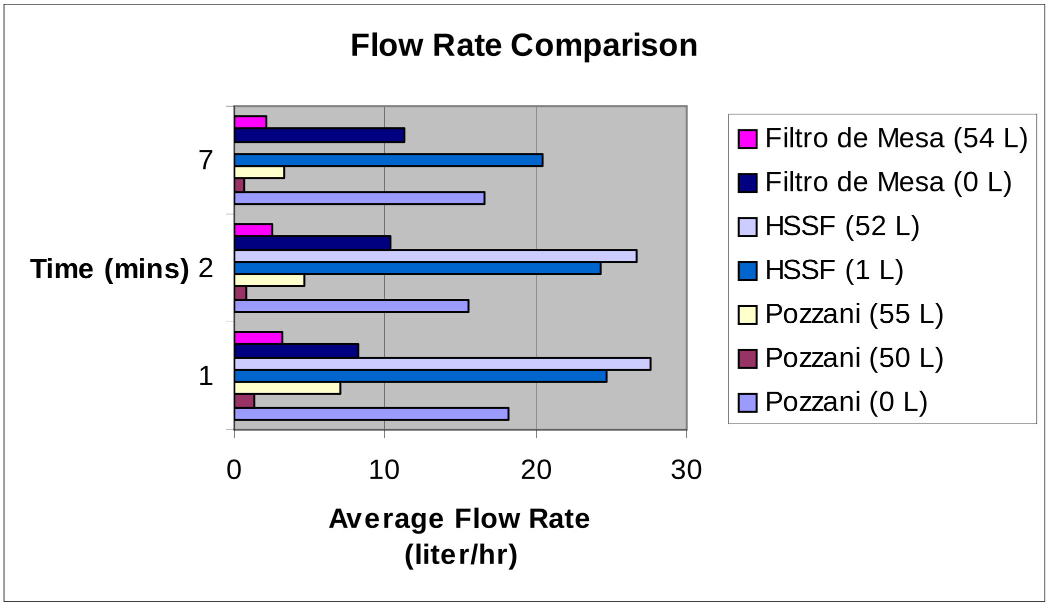


Figure 34: Comparison of the Pozzani, HSSF, and Filtro de Mesa flow rates.

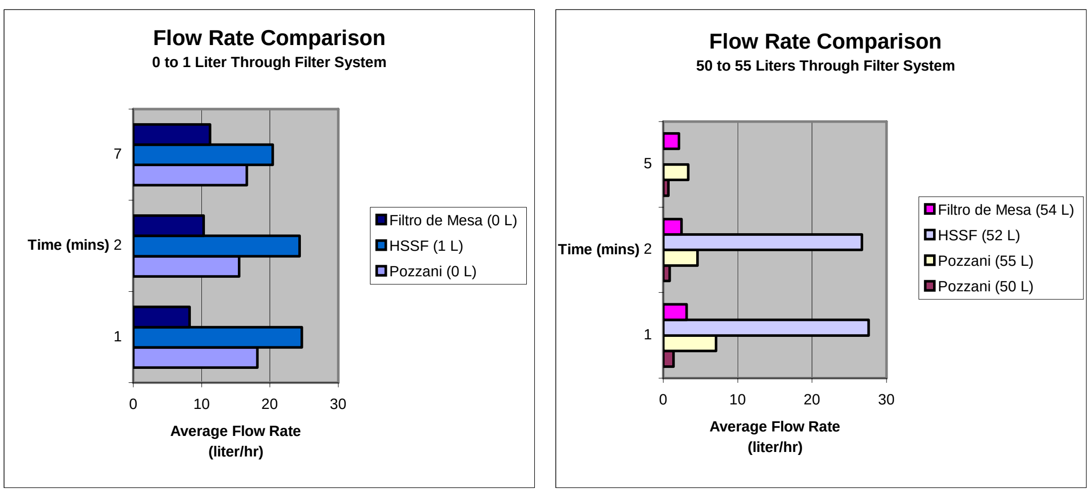


Figure 35: Flow rate comparisons of Pozzani, HSSF, and Filtro de Mesa. The left displays a fairly new filter, where little water has passed through the filter. The right displays a used filter where multiple liters of water have passed through the filter.

Initially, (at 0-1 liter) the HSSF has the fastest flow rate (~22 L/hr), followed by the Pozzani (~17 L/hr), and then the Filtro de Mesa (~10 L/hr). After use the HSSF maintains its high flow rate, while the flow rates of both the Pozzani and Filtro de Mesa systems decline.

4.4.4 Cost

The table below provides the cost of components for each filter system. The total cost is just the total of the components. It does not include the cost of tools to construct the filters, time to assemble, importation and handling fees.

Table 6: Cost comparison of the filter systems.

Filter System	Components	Cost	Total
Pozzani	2 HDPE Pails	$12.00	$15.00
	2 Ceramic Candles	$3.00	
Katadyn	2 HDPE Pails	$12.00	$30.00
	2 Ceramic Candles	$18.00	
Filtro de Mesa	Sand**	$0.00-$1.00	$17.00-$22.00
	2 HDPE Pails	$12.00	
	Geotextile*	$1.00-$3.00	
	Rubber Ring*	$1.00-$3.00	
	2 Ceramic Candles	$3.00	
HSSF	Gravel**	$0.00-$1.00	$10.00-$13.50
	Course Sand**	$0.00-$0.50	
	Fine Sand**	$0.00-$1.00	
	PVC	$1.00	
	Diffuser Pail	$3.00	
	Fabric/Textile**	$0.00-$1.00	
	1 HDPE Pail	$6.00	

Notes:
* cost is uncertain
** item could be free

While the HSSF might be the least expensive option it is also the most time consuming to construct and also requires more tools to build than the other systems. Yet a highly beneficial aspect of the HSSF is that all of its components can be obtained locally. The Katadyn system contrasts with the HSSF as the most expensive. The Katadyn is also not marketed in Peru, which means that once the candles reach the end of their lifetime or are broken it will be more difficult for the locals to obtain replacements. However, the alternative ceramic candle system, Pozzani, is marketed in Peru and is half the price of the Katadyn system. The fragility of the ceramic candles can be problematic since this leads to breakage. Broken candles increase the total cost of filter operation due to the increased frequency of purchasing replacement candles. The lack of candles in the HSSF makes the system more robust, as long as a proper fitting is obtained for the PVC spigot. The robustness of the pails is a major benefit in all cases.

4.5 Experimental Error

Influent Experimental Error for all four filters was 38% error for the 10-170 range analysis and 40% for the 20-80 range. The team chose to evaluate experimental error as pooled relative error in order to weight the data that had higher volumes filtered, data in which there would be greater confidence attributed to the determination. Bioassay experiments typically have higher experimental errors. Individual replicate determinations in the 20 -30% range are considered typical error results for the tests that were performed.[20]

The team attributes primary error sources to the testing procedures including: inadequate mixing and settling of the water filter samples, dilution and colony identification. The MIT team also used lauryl sulphate growth medium, which needs to be refrigerated and kept in a dark place to ensure its performance. During days when the team conducted two rounds of microbial testing, they would use lauryl sulphate all day long, without refrigerating the growth medium. It is unclear to what extent, if any, its potency was compromised.

Interestingly, when comparing individual filters and their respective experimental errors, samples taken from Katadyn and Pozzani have higher experimental errors than the samples taken from the HSSF or the Filtro de Mesa. A table of individual filters' experimental errors for both ranges are displayed below.

Table 7: Experimental Error for microbial contamination influent data obtained from testing four home water filtration filters; June and July, 2004.

Experimental Error* for individual filters	**Percent Error 10-170 CFUs counted**	**Percent Error 20-80 CFUs counted**
HSSF	21%	24%
Table Filter	30%	20%
Pozzani	72%	56%
Katadyn	34%	57%
Average Experimental Error	38%	40%

*Experimental Error expressed as Pooled Relative Error

Influent collection methods varied for the HSSF and the Filtro de Mesa versus the Pozzani and Katadyn ceramic candle systems. Due to the more rapid flow rate of the HSSF, the person collecting the sample would often rush to collect the sample from the top pail of the filter. Due to the slower flow rate of the Katadyn system, rushing was not necessary. The lag time in influent sample collection for the Katadyn system may have allowed for some settling out of microbes from the top half of the water column, where the samples were typically drawn.

This report includes both the range of 20-0 colonies counted used in *Standard Methods* for determining microbial contamination as well as the 0-200 colonies range. The team decided to enlarge the range beyond what is called for in *Standard Methods*, so as to increase the data from which the report draws its conclusions, and to increase the degrees of freedom for repeat sampling. The team believed that the error introduced from small samples and the error from overcrowding in larger samples would be outweighed by the benefits of a fuller data set. Given the limited instances of testing, approximately 10 data points per filter under the 20-60 CFUs

[20] Brown, L.C. "CE-32 Lab Bacteriology Notes", Spring 2004, P. Bacti-8. Tufts University CE-32., Department of Civil and Environmental Engineering

counted, enlarging the range of acceptable data points doubled the size of the 0-200 data set, on average. Enlarging the data set did not enlarge the experimental error. One of the greatest challenges of conducting these filter tests was predicting the concentration of microbial contamination for samples on different days. Even with six week's worth of microbial contamination characterization for samples taken from households and canals in La Joya, CBV, and samples from the Rio Chili, the contamination levels substantially varied on a day-to-day basis. Additionally, water samples were left unrefrigerated in the laboratory. Since filter performance was evaluated by relative microbial removal, this did not affect filter performance; however, it did affect the team's ability to predict contamination levels based on the prior day's results. Sudden microbial die-off caused an entire set of tests to be discarded on one day, while on other days the contamination levels remained constant.

5.0 KX/FirstWater Investigation

5.1 Introduction

In addition to the MIT study, the MIT team also assisted in a study led by FirstWater, a small business which investigates and supplies point-of-use drinking water solutions to communities, government agencies and NGOs throughout the developing world. This KX filter study was led by Thomas Clasen, the founder and managing director of FirstWater and Sophie Boisson, an MSc candidate at the London School of Hygiene and Tropical Medicine.

5.2 Overall Objective

The purpose of the KX study was to test the performance and epidemiological effects of the integration of a point-of-use water filtration system using a new filter medium developed by KX industries. The filter uses carbon nanotechnology and was first developed and tested in KX laboratories in Connecticut, USA. After laboratory testing, the manufacturer wanted these new filters tested in-situ. Assuming field laboratory testing would show negligible malfunctions, adequate flow rate, and sufficient bacteria removal, the filters would be distributed as part of a small pilot test. The pilot test would recruit 80-100 families in a community whose water supply is thought to be extremely contaminated for this study. If the filter systems proved effective in the households, the company would then be confident in funding an epidemiological outcome test in other locales.

5.3 MIT Team Objectives

The MIT team's work was very much the preliminary stage of the study, that is, to identify and recruit a community to take part in the study.

- Carry out interviews and take samples from households in La Joya and Cerrito Buena Vista (CBV) to better characterize drinking water and water practices within the home in order to provide more information relevant to the performance of the KX filter medium.
- Conduct bench testing of KX filter elements with a range of water from La Joya and Buena Vista in order to evaluate filter performance under simulated field conditions.
- Based on sampling results, choose one of the two communities to be recruited for the study
- Recruit 100 households from the chosen community to participate in the pilot study, and obtain their written consent for participation.

Following the MIT part of the investigation, Tom Clasen and Sophie Boisson distributed the filters and carried out the remainder of the study. For more detailed information on the research and events concerning this study see appendix 3, 4, and 5 (the MIT team's timeline, Thomas Clasen's protocol for the pilot study, and Sophie Boisson's thesis).

6.0 TestWaterCheap Investigation

The purpose of this exercise was to test in-situ performance of a new membrane-filtration unit, "TestWaterCheap", and its ability to detect the quantities of thermotolerant coliform present in water; and to provide qualitative feedback on the experience of operating the TestWaterCheap technology in-situ.

6.1 The Technology

The TestWaterCheap device is a cheaper water quality testing device whose technology was drawn from the Millipore system. The water receptacle is a sterile drop-in instead of the sample collection bag. The TestWaterCheap device adds a cost of a few pennies to each test (which costs approximately $2 for any membrane filtration system); the drop-in gives a better seal and allows the accurate use of a 100mL sample. While commercially-available laboratory pump filters can cost $1000, the TestWaterCheap device is estimated to cost $13 to construct.

The TestWaterCheap assembly design, shown in figure 35, consists of inexpensive and readily available or easily manufactured parts. The device uses a baby bottle with disposable drop-in inserts as the base design. The inserts allow for easy "drop-in" convenience and have a semi-rigid and smooth top lip, which allows the insert and filter paper to rotate freely when the lid is screwed on, avoiding shear forces. The apparatus is assembled with the bottle "upright" so that water does not spill out. The entire apparatus is then inverted after it is fully assembled so that the water rests on top of the filter paper.

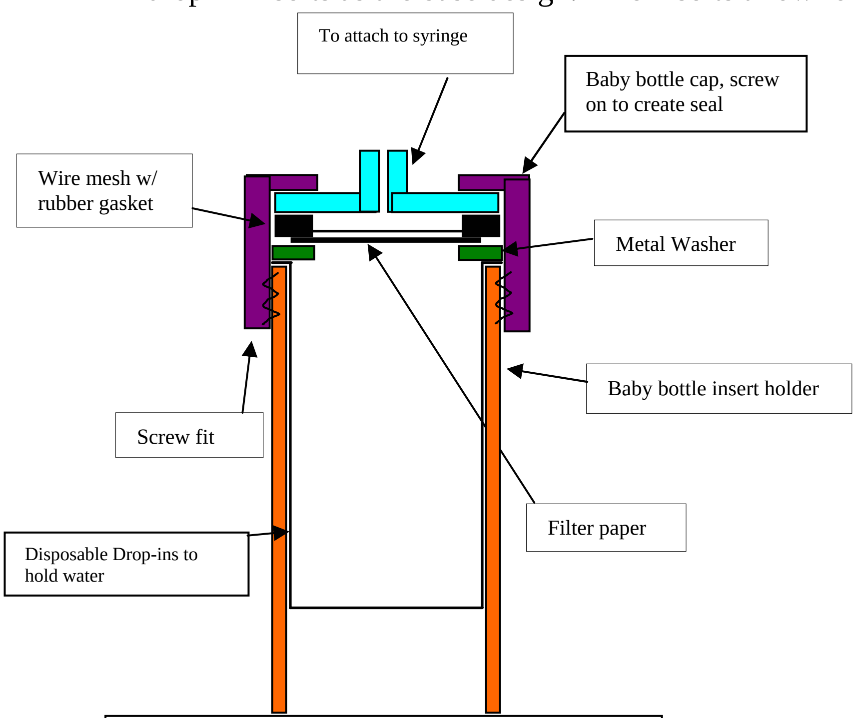


Figure 36: Schematic of TestWaterCheap.

Steps to membrane filtration using TestWaterCheap device (Figure 36):

1. A sterile insert is dropped into the rigid plastic bottle/holder.
2. The water sample to be tested is poured into the disposable insert.
3. A metal washer is placed on top of the disposable insert.
4. The filter paper is then placed on top of the metal washer (the metal washer is necessary to prevent the filter paper from falling into the insert; the washer is flamed so that it is sterile).
5. A fine metal mesh is placed on top of the filter paper.
6. A rubber washer is placed on top of the mesh to create a tight seal between the washer, mesh, filter paper, and drop-in insert when the lid is screwed on the top.
7. The "lid" is actually a ring that screws on to the top of the bottle. A rubber nipple is usually placed inside this ring for feeding infants. Instead of this nipple, users place a plastic disk with a spout sticking out (made from a plastic wash bottle lid) through the bottle's ring. It is through this spout where the filtered water will flow out. These two pieces are screwed tightly on to the top of the bottle, sealing the filtering mechanisms.
8. A rubber tube is attached to this spout.
9. A syringe is then attached to this rubber tube.
10. The entire assembly is inverted and the tester uses this syringe to apply a vacuum to pull the water through the filter paper.

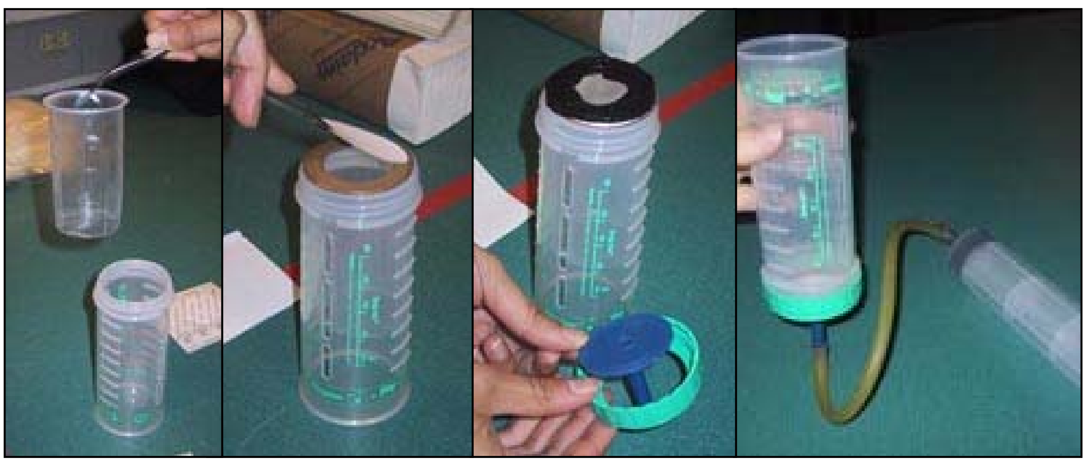


Figure 37: Use of TestWaterCheap. Photos from TestWaterCheap.

Between each test the insert is discarded and traded for a sterile one, and the mesh and metal washer are sterilized in alcohol and/or flame. A new filter paper is used for each test. The other parts of the assembly do not need to be sterilized because they do not touch the sample water before it touches the filter paper, nor do they touch the middle of the filter paper where the bacteria colonies will be grown. The metal mesh and rubber washer may need to be sterilized only at the beginning of each testing session (e.g. only once per testing day). This will be verified through further testing.

As with all membrane filtration tests, after the above steps are completed, the filter paper is removed from the assembly and placed in a Petri dish with growth medium that feeds any bacteria. The dish is incubated for 24 hours and the bacteria colonies are counted to identify the level of bacteria contamination in the water sample.

6.2 Experimental Design

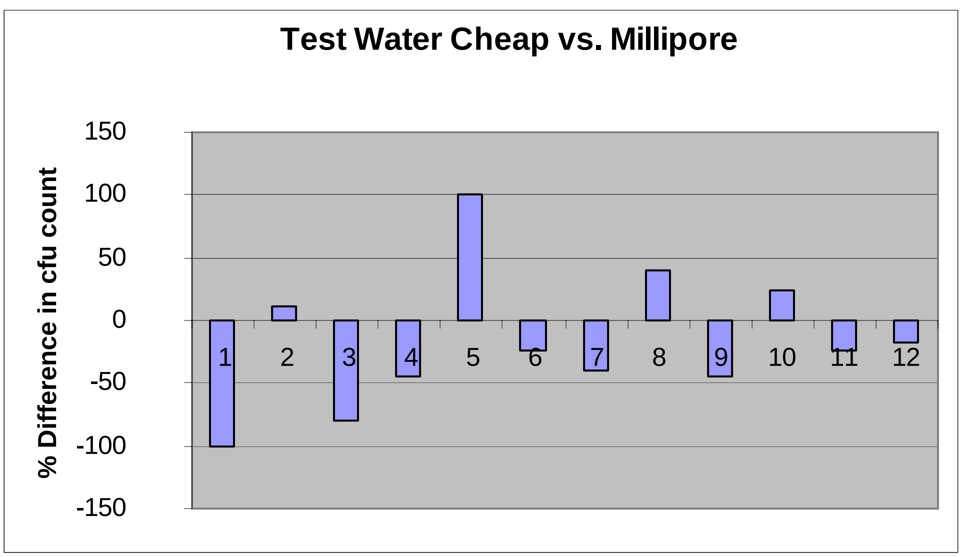
The MIT research team tested pre-treatment water (the same water as was used in the filter studies) from the rivers, canals, taps, and homes in the Department of Arequipa, Peru for thermotolerant bacteria using Standard Method 9222- D.[21] 100 milliliters of sample water was pumped through a membrane filter using commercially-available filtration pumping devices.[22] The process was repeated using the same sample water and quantity for the TestWaterCheap device. The results from the commercially-available Millipore filtration units were used as the baseline from which to compare the performance of TestWaterCheap filtration unit.

Sample water was collected and dispersed using the methods described in Section I. All tests were performed using a Lauryl Sulphate Broth prepared in the same manner as previously mentioned.

6.3 Results and Discussion

The results are inconclusive due to the limited amount of data for TestWaterCheap and the high variability and standard error for the baseline data.

The table in appendix 5 shows varying volumes of water filtered and the test results from when the Millipore filtration unit was used and when the TestWaterCheap filtration unit was used. When the research team tested repeat volumes, the average was used for comparison. Figure 37, below displays the percent difference between the Millipore unit and the TestWaterCheap unit. The difference is based upon the number of thermotolerant colony forming units, CFUs per 100ml.



[21] Standard Methods, 20th ed. (1998)

[22] Millipore, Catalog number: XX6300120 and the filter pump included in Oxfam's Del Agua Kit. No differentiation was made as to which commercially-available pump was used in the data set.

Figure 38: The percent difference between Millipore and the TestWaterCheap filtration units. The x-axis is the test number and the y-axis the percent difference.

Using the Millipore results as a baseline to compare TestWaterCheap results, figure 37 shows that the TestWaterCheap filtration unit yields higher CFU counts for four trials (as in trial numbers 2, 5, 8, 10), and lower CFU counts for 8 trials. Yet, by examining the high experimental error, as displayed below, and acknowledging the variability associated with TTC tests in general, it is evidenced that the results should be taken lightly and deemed inconclusive.

6.4 Experimental Error

For TestWaterCheap experiments, microbial results from using TWC apparati were compared to the results from using Millipore filtration units. For this report, data that fell between 0-200 colonies counted range was considered. Eliminating data that fell out of the *Standard Methods* 20-60 colonies counted range would have resulted in too small of a data set for interpretation. As noted in previous sections of the report, the research team had difficulty predicting the extent of microbial contamination and thus adjusting the volume of sample water filtered, to keep results within the 20 – 60 colonies counted range. Experimental Error is expressed as pooled relative error. For the sample data set comparing TestWaterCheap and commercially available filtration pumps, the error was 48% and 20% respectively. The variability of the TWC data was 60% higher than the variability for the data utilizing commercially available filtration units. There was no significant bias for TWC. Figure 37 displays the results of TWC data relative to the data collected using Millipore filtration units.

Sources of error include the error typically associated with these tests: inconsistent growth medium makeup or usage, improper dilution, error from colony counting, etc. However, these errors should be found in both TWC and the data collected using commercially available filtration units. Additional error for TWC data could have resulted from TWC not properly performing and filtering all of the sample volume through. Researchers would often see small drops of sample lining the plastic baby bottle bag that had not been sucked through despite pumping. Furthermore, the lack of a holding apparatus and the occasional difficulty in establishing an adequate level of suction created instances where the baby bottle was not held fully upright. Researchers would often anchor the pump underneath the armpit while inducing suction. Lastly, upon visual inspection, the screen, rubber seal and the filtration papers were not uniformly matched. It is unclear if the apparatus allowed for sample leakage by circumventing the filtration. To reduce TWC experimental error for future experiments, the team recommends developing a holding apparatus for the TWC so that an individual could perform the test by him- or herself without using an arm to cradle the bottle. Alternatively, TWC could standardize the holding position of the bottle during suction. Using samples with less variable microbial contamination would reduce the error associated with both the control and the TWC data.

The final recommendation for evaluation TWC performance is to evaluate the apparatus' performance with a larger data set. One could be better able to conclude if error was random error or attributed to TWC.

Table 8: Comparison of Variability and Experimental Error for data collected using commercially-available pumps and TestWaterCheap Pumps, during experiments conducted throughout July, 2004; Arequipa, Peru.

	Results from Commercially Available Pumps	**Results from TestWaterCheap Pump**
Pooled Standard Deviation	1025	1681
Pooled Relative Error	20%	48%

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Appendix 1: Pre-departure MIT laboratory CEE data from Robert Malies

Table 1: TTC tests performed on the HSSF by an MIT student, Robert Malies, prior to the research team's departure to Peru.

Date	Filter	Before	After	After (for calc)	% Reduction	LRV	Coliform Type
2/25/04	HSSF	2.80E+03	4.15E+02	4.15E+02	85.18	1.29E-01	Total coliform
2/27/04	HSSF	9.70E+03	2.40E+02	2.40E+02	97.53	1.61E+00	Total coliform
3/3/04	HSSF	2.90E+04	3.55E+02	3.55E+02	98.78	1.91E+00	Total coliform
3/4/04	HSSF	2.90E+04	3.70E+03	3.70E+03	87.24	8.94E-01	Total coliform
3/5/04	HSSF	7.00E+04	4.70E+03	4.70E+03	93.29	1.17E+00	Total coliform
3/5/04	HSSF	1.00E+03	7.00E+02	7.00E+02	30.00	1.55E-01	Fecal coliform
3/6/04	HSSF	2.00E+03	0.00E+00	1.00E+00	100.00	3.30E+00	Total coliform
3/6/04	HSSF	1.00E+03	0.00E+00	1.00E+00	100.00	3.00E+00	Fecal coliform
3/19/04	HSSF	1.00E+02	2.00E+01	2.00E+01	80.00	6.99E-01	Fecal coliform
4/12/04	HSSF	1.00E+03	0.00E+00	1.00E+00	100.00	3.00E+00	Total coliform
4/15/04	HSSF	6.00E+03	2.00E+00	2.00E+00	99.97	3.48E+00	Total coliform
4/16/04	HSSF	6.00E+03	0.00E+00	1.00E+00	100.00	3.78E+00	Total coliform
4/20/04	HSSF	4.50E+03	2.40E+01	2.40E+01	99.47	2.27E+00	Total coliform
AVERAGE	**HSSF**	**1.25E+04**	**7.81E+02**	**7.81E+02**	**9.01E+01**	**2.01E+00**	**Total coliform**

Table 2: Turbidity tests performed on the HSSF by an MIT student, Robert Malies, prior to the research team's departure to Peru.

Date	Filter	Before	After	% Reduction
3/4/04	HSSF	6.26	1.46	76.68
3/5/04	HSSF	6.51	1.58	75.73
3/6/04	HSSF	3.5	0.7	80.00
3/10/04	HSSF	5.34	0.57	89.33
3/19/04	HSSF	9.83	0.2	97.97
4/12/04	HSSF	11.85	0.3	97.47
4/20/04	HSSF	7.4	0.6	91.89
Average	**HSSF**	**7.24143**	**0.7729**	**87.01**

Appendix II: All Data Collected in Peru

Insert 17 Excel Data Sheets

Appendix III: Thomas Clasen's Protocol

HOUSEHOLD DRINKING WATER TREATMENT IN PERU USING GRAVITY FILTERS WITH LAMINATED CARBON FIBER MICROBIAL BARRIER

PROTOCOL FOR A PILOT STUDY

Thomas F. Clasen
London School of Hygiene & Tropical Medicine

A . Background and Rationale

Diarrhoeal diseases kill an estimated 2.5 million people each year (Kosek 2003). Among children under 5 in developing countries, diarrhoeal disease accounts for 21% of all deaths (Parashar 2003). By inhibiting normal consumption of foods and adsorption of nutrients, diarrhoeal diseases are also an important cause of malnutrition, leading to impaired physical growth and cognitive development, reduced resistance to infection, and long-term gastrointestinal disorders. In Peru, diarrhoea is the second leading cause of death in children under 5 (Unicef, 1998).

Ingestion of unsafe water, along with inadequate availability of water for hygiene and a lack of sanitation, account for 88% of deaths from diarrhoea (WHO 2002). According to the WHO/Unicef 2000 assessment, only 54% of the rural population in Peru have access to improved supplies of drinking water, the lowest in all but two countries in the Americas (WHO/Unicef, 2000).

While the delivery of safe, reliable and affordable water services to people in developing countries is an essential long-term goal, there is an alternative way to achieve much of the health benefit of safe water. A WHO-sponsored review of these interventions concludes that "there is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically improving the microbial quality of household stored water and reducing the attendant risks of diarrhoeal disease and death (Sobsey 2002). This is the basis for the WHO's *International Network to Promote Household Water Treatment and Safe Storage*, a public-private partnership announced at the Kyoto World Water Forum in March, 2003.

Among the "most promising and accessible" of the technologies for household water treatment identified by the WHO is ceramic filtration (Sobsey 2002). In a recent study in Bolivia, gravity filters incorporating ceramic media were effective in eliminating faecal bacteria and reducing the prevalence of diarrhoea by 64% (Clasen, 2004). These filters have certain advantages over other household-based water interventions, such as chlorination and solar disinfection, especially in water of medium or variable levels of turbidity. However, ceramic filters, which rely on mechanical removal of pathogens by depth filtration, have not been yet met the EPA standard for removing 4 logs (99.99%) of waterborne viruses. Rotavirus, which may be waterborne, accounts for up to 40% of hospitalizations for acute watery diarrhoea, and approximately 500,000 deaths per year.

In Peru alone, rotavirus is responsible for 384,000 cases of diarrhoea per year in children under 5, leading to 64,000 clinical visits and direct medical costs of approximately $2.6 million (Ehrenkranz, 2001). Hepatitis A and E are also important waterborne pathogens. Except for more expensive flocculant/disinfection combinations, none of these household-based water treatment technologies remove chemical contaminates such as arsenic, nitrates or harmful organics from pesticides and herbicides.

Activated carbon is the most common medium for the point-of-use treatment of water in developed countries. Unlike ceramics and other media which remove pathogens by microfiltration, activated carbon "adsorbs" microbes and other pathogens, including certain harmful chemicals, by attracting them to its surface and trapping them in microscopic pores. Thus, they are potentially effective not only in removing protozoa and bacteria, but also viruses and chemical contaminants. Traditionally, however, activated carbon alone has not been used for the treatment of microbiologically unsafe water over time. Dissolved organic matter in the water can quickly take up adsorption sites, exhausting the medium's capacity. The cost of replacing the medium, and the difficulty in knowing when such replacement was necessary, made such filters impractical for the microbiological treatment of water over the long term. Moreover, in the absence of bacteriostactic agents, carbon can be also be colonized by heterotropic plate count and even faecal bacteria that could subsequently be shed into the product water.

B. The Filter Intervention

The filter system to be evaluated in this pilot study consists of a newly-developed laminated carbon fiber microbial barrier mounted into a double-chamber gravity filter designed for household use. This advanced filter medium represents a potential breakthrough in household water treatment. The multi-layer flat medium consists of (1) a 10-25 micro fiber pre-filter for advance dirt-holding capacity, (2) a layer of chemically-treated pulverized activated carbon for adsorption of natural organic matter (NOM), and (3) a final nanofiber barrier treated with cationic silver halide. Independent testing has shown the medium effective in meeting the US EPA guidelines for microbiological purifiers, which require reductions of >99.9% of protozoan cysts, >99.9999 percent of bacteria and >99.99% of viruses.

In addition to its viral reduction capability, the medium addresses the main shortcomings of conventional activated carbon. Fabricated on a high-speed press, the medium can be produced at costs per liter treated that are competitive with other household-based water treatments such as chlorination and ceramic filtration. The chemistry of the protective activated carbon structure is designed to form a gel within the pores between the grains of carbon when the concentration of NOM exceeds the adsorption capacity of the carbon. This effectively shuts down the filter and alerts the user to the need to replace the filter medium. Depending on the size of the filter disk in use and the source water conditions, the filter disk would need replacing after treating approximately ___L (or roughly one month's use by a family of 5). The silver halide serves as a bacteriostatic agent, thus preventing colonization of the medium. While the chemistry of the filter medium is damaged when exposed to water-dispersed anionic polymers such as humic and

fulvic acid, it is believed that such acids will rarely affect performance in actual field conditions.

The filter medium is mounted into a blow-molded drip filter, consisting of a 10L chamber for source water and a 20L chamber for product water. These are sized to provide sufficient water for drinking, cooking and cleaning cooking and eating utensils. When the upper unit is filled, water passes through the filter medium and into the lower chamber where it is protected against recontamination and accessed solely by a tap that even young children can use. The system is designed to treat approximately 3L/hour; larger or multiple units can be used as necessary to treat larger volumes.

Intervention households will be instructed in the proper assembly, use and maintenance of the filter system, and will be encouraged to use only filtered water for drinking, washing fruits and vegetables and preparing foods, and washing cooking and eating utensils. No hygiene or other instructions will be provided as part of the intervention.

C. The Study Site

[to be completed]

D. Objectives of Pilot Study

The objectives of the study are to evaluate 1) the performance of the filter system in improving the microbiological quality of water during household use, 2) the use and maintenance the filters by the study population under field conditions, 3) the acceptability of the filter system among the study population, and 4) the affordability of the system to the target population.

E. Description of the Pilot Study

The pilot study will be managed by Thomas F. Clasen, a lecturer at the London School of Hygiene and Tropical Medicine. He will be joined by one or more MSc students from the London School. Joseph Brown, a PhD student at the School of Public Health, University of North Carolina, will conduct the acceptability and affordability assessment. The filter systems will be donated by the manufacturer, KX Industries, LP, which is also providing financial support for the pilot. [Local partner, local investigators to be completed]

1. Recruitment and Consent. **80-100 households will be recruited from the community to participate in the study. After being given full details of the study and its objectives, the head of household will be asked to consent in writing to participate.**

2. Baseline Survey**. Prior to the commencement of the study, a baseline survey will be conducted. The head of each household will be interviewed about family demographics, household possessions (as a measure of estimated wealth), water source, water handling**

practices, and knowledge of diarrhea prevention. At this time, water was also sampled from the bucket, jerry can, pond or other source that the participants reported to be their source of drinking water that day.

3. Randomized Allocation. **Following the baseline survey, participating households will be randomly assigned into two groups. Half of the households will receive filters and instructions about their use; the other half of the households will serve as a control group and continue to use their customary drinking water practices.**

4. Water Sampling, Use and Maintenance. **Within one week of the distribution of the filters, an investigator will visit each intervention household and answer questions. Thereafter, an investigator will visit each intervention household on a weekly basis for 6 weeks to take water samples to quantify the extent of faecal coliform (FC) and *E. coli* in the product water, to measure pre- (and in the case of intervention households, post-) filtered turbidity (NTU) and inquire about water aesthetics (colour, odour, taste). Intervention participants will also be asked about frequency of filling, use and maintenance of the filter system.**

5. Water Quality Assessment. **Water turbidity will be measured by a portable meter (2100P Portable Turbidimeter, Hach Company, Loveland, CO). For bacterial assessment, 125 ml water samples will be collected in sterile Whirl-Pack™ Bags which will be placed on ice and processed within 4 hours of collection. Processing will be performed using the Colilert™ Quantitray 2000 kit (IDEXX Laboratories, Inc., Westbrooke, ME). Media reagent is added to the water samples and shaken until dissolved. The sample mixture is then poured into the Quantitray, sealed and incubated for 24h. The trays are then analyzed for color change (FC) and fluorescence (*E. coli*).**

6. Acceptability and Affordability. **After 4 weeks, participants will filters will also be asked to complete information from a standard questionnaire on acceptability and affordability (willingness to pay). A random sample of the female heads of household will also be asked to participate in focus groups to obtain information on acceptability and affordability.**

7. Confidentiality; Medical Referral. **All data will be treated confidentially. Investigator will assign a number to all participants and information will thereafter be recorded by this number only, with no disclosure of identifying information. Medical supervision will be provided by the health clinic operated by the Local Partner. Investigators making weekly visits to households will refer any observed conditions to that clinic.**

8. Communication of Results; Sustainability. **Following the completion of the study, the results of the microbiological and other outcomes will be communicated to all study participants at a meeting called for that purpose. If the filter has been effective in improving the microbiological quality of water in the homes, control group households will be offered their own filter. Investigators will then work with the local partners to ensure**

that study participants and others who wish to procure filters and filter media can do so at affordable costs.

9. Data analysis. **Epi Info will be used for descriptive and univariate data analysis. Stata will be used for additional data analysis, including comparisons of intervention and control households using Fisher's exact t-tests.**

Appendix VII: First Water Pre-Pilot Study Plan

FIRST WATER/MIT

PRE-PILOT WORK PLAN FOR LA JOYA DISTRICT

June 2004

Week 1 (May 31-June 4): Survey and Water Characterization

Objective: To better characterize drinking water in La Joya and Buena Vista in order to provide more information relevant to the performance of the KX filter medium.

Tasks:

- **Obtain additional information on the sources of the water delivered to households in La Joya and Buena Vista. We understand that this is from various irrigation canals that have their origin in the Rio Chile. Describe and illustrate the flow from the households to the river or other surface sources. Some of this information may be available from previous MIT work at in the La Joya District**
- **Determine if there is a reasonably up-to-date map of the La Joya and/or Buena Vista showing streets, etc. which could be used to develop a sampling plan. If not, prepare a rough map for that purpose.**
- **Obtain any available demographic information from local governmental or medical authorities**
- **Develop a sampling plan for each community**
- **Use the sampling plan to obtain up to 16 household samples each day and at least 30 total samples, half from each of the two communities. These samples should normally represent the water in the home that is used for drinking. In some cases, this water will have been boiled or otherwise treated; in other cases, it will not. The sample should be taken from the vessel, tap, hose or other source that is used to fill a drinking cup. It should not come directly from the drinking cup itself. There is no need to flame or otherwise sterilize the tap or other source. Of course, the sampling bottles should be sterile (boiled) in advance.**
- **Record information on the name and address of the household and the number of inhabitants, whether or not the householder treated the water, where the householder understands the water came from, how much the householder pays for the water and an estimate of how much water is used.**
- **In addition, conduct tests for turbidity (NTU with Hach 2100P), pH and residual free chlorine (with DelAgua comparator). If you have any other equipment to test other parameters, use these as well and report on these additional tests.**
- **Arrange for TOC testing per a sampling plan to be recommended by MIT colleagues in Arequipa.**
- **Report thermotolerant (fecal) coliforms (TTC) per 100ml. You may need to dilute down to 1ml of sample water to obtain a plate that has countable colonies.**

Week 2 (June 7-June 11): Construct and Bench Test Filters

Objective: To conduct bench testing of KX filter elements with a range of water from La Joya and Buena Vista in order to evaluate filter performance under simulated field conditions.

Tasks:

- **Collect the 6 filter elements that KX is to courier to Fr. Alex on May 28. Make sure these are marked serially to keep track of them.**
- **Purchase 6 transparent 20L HDPE graduated pails with lids in Arequipa (we priced these at Loceria "Yoselin" (Dean Valdivia No 320, phone 285450) at S/20 each including taps for the bottom 3 buckets. You may also need to find fittings and rubber washers.**
- **Construct prototype filter units with KX elements and buckets/lids/taps. Make sure they are water tight. Record how you construct them and take some digital pictures**
- **Develop a sampling plan that represents the range of water parameters that you encountered from the previous week. This may, for example, be divided into a "normal", "challenge 1", "challenge 2", etc. set of waters; it is important, however, that the waters used for the actual bench tests reflect the various parameters likely to be encountered in the field. Record the parameters of each of these water samples.**
- **Using this range of water samples, test the performance of the filters. You may want to set up two at a time so that you can duplicate your results and report an average. The parameters you should assess are the following (and any others you deem relevant):**
    - **Flow rates. Since this will vary with head pressure, you will want to record results when the top bucket has various levels of water. It will also vary with dirt load. Again, this is something that we want to measure. Record results and construct tables and graphs showing results.**
    - **Microbiological Performance: Collect before/after samples (top bucket and bottom bucket) and analyze for TTC.**
    - **Chemical Removal. If you have the capability of testing for the filter's ability to remove chemical contaminants, please do so and report.**
    - **Longevity: Finally, try to assess the longevity of the filter (ie, its capacity for treating a given volume of water using the various challenges. Note, however, that whereas the filter elements you receive and test are not cleanable, the ones to be used in the field are. You will test this aspect of performance after the trial begins.**

Week 3 (June 14-18): *Prepare and submit initial reports*

Use this period to complete any remaining work from weeks 1 and 2 and to prepare and submit to T. Clasen your report on the above.

Week 4 (June 21-25): Recruit participating households for pilot study

<u>Objective</u>: To recruit 100 households to participate in the pilot study, and to obtain their written consent for participation per the study protocol.

<u>Task</u>:

- **Based on the results from above, we will decide whether to conduct the study in La Joya, Buena Vista or both.**
- **Determine if there is a list of the households in the study community that can be used to randomly select households to be contacted for possible inclusion in the study. If not, use another method to be agreed to randomly select candidate households. This should not be done by self selection of interested householders.**
- **Visit the randomly selected households and use the attached form to provide details of the study. Make sure they understand all relevant details, including the fact that only half of the participants will receive the filters at the outset of the study, and the others at the conclusion of the study. Ask if they have any questions. When any questions have been answered, ask the head of household (male or female) to sign the informed consent form. Finally, tell them about the place and time of the public meeting described below and make sure they attend.**
- **Prepare a list by name, address and any other important identifying information of all 100 participating households. This list must be ready by June 25, 2004.**
- **We expect to hold a meeting of all 100 participating households at a convenient time between June 25 and 28. At that meeting, we will hold a public lottery to allocate households to the intervention and control groups. We will then ask the intervention households to stay for an extra hour to receive their filters and learn how to assembly, use and maintain them and answer questions before they return to their households with their filters.**

NB: Until the filters have been proven in this field pilot and in all lab tests to eliminate all known waterborne pathogens, we will ask all participants to continue to boil or otherwise treat water that has been passed through the filter. While we expect this to be superfluous and perhaps difficult to explain to the intervention households given the purpose of the filter to replace any such alternative treatment, it is necessary until the filter has been proven to be a safe alternative to such treatment. Consistent with the study design, since we will thus be asking even filter users to follow their existing practices, this study will not present useable health impact data.

Attachment A

[Statement and Consent]

Ensayo controlado con filtros de gravidad para potabilización de agua

Consentimiento y acuerdo para participar

Mucho gusto, mi nombre es _____________ y trabajo con la Escuela Londres de Higiene y Medicina Tropical. Como usted sabe, la diarrea es un problema muy serio en Perú, pues ésta causa muchos malestares, incluso puede causar la muerte, particularmente en los niños más pequeños. Es muy común que la diarrea se produzca por beber agua contaminada. Su comunidad ha sido seleccionada para participar en un proyecto que determinará la efectividad de filtros mejorando la calidad del agua. Nos gustaría evaluar el filtro para ver si este puede mejorar la calidad del agua en su comunidad. Este proyecto de investigación lo está desarrollando la Sociedad Misionera de San Pablo, el Instituto de Investigación Nutricional, el Instituto de Tecnología de Massachussets y la Escuela de Higiene y Medicina Tropical de Londres. En las próximas seis semanas, nos gustaría probar que tan bien trabaja el filtro mejorando el agua que usted y su familia beben. Para hacer esto necesitaremos la ayuda de familias que viven en su comunidad, si usted está de acuerdo en hacer parte de esta investigación, le solicitamos hacer lo siguiente:

- ✓ **Primero, haremos preguntas acerca de usted y de los miembros de su familia, de cómo se abastece de agua, sus prácticas de saneamiento e higiene y de cómo manipula el agua. Esas preguntas tardarán máximo 15 minutos. Luego nos gustaría tomar algunas muestras de agua de sus recipientes para probar la pureza, esta visita durará entre 15 y 20 minutos.**
- ✓ **Segundo, haremos un sorteo para seleccionar la mitad de las familias, quienes recibirán filtros. Necesitamos que la mitad de las familias sigan consumiendo el agua con las mismas prácticas de siempre para comparar el agua filtrada con el agua que tradicionalmente han usado. Pero, por razones de seguridad, auque las familias con filtros deben que seguir las mismas prácticas de siempre de tratar agua de beber a lo menos confirmar que los filtros operan bien. Les mostraremos a las familias seleccionadas como usar y cuidar el filtro, también les haremos seguimiento y nos aseguraremos que los filtros estén operando satisfactoriamente y que responde a nuestras preguntas.**
- ✓ **Tercero, en el curso de los seis semanas de estudio visitaremos a cada familia participante cada semana para preguntar por la uso del filtro y tomar la muestra de agua para el análisis. Luego de algunas semanas, haremos algunas entrevistas adicionales para aprender más acerca de la aceptabilidad de los filtros y como podrían ustedes tener uno de manera permanente.**
- ✓ **Al final de la evaluación, proveeremos a ustedes la información completa de los resultados del estudia. Las familias que ayudaron con el estudio van a conservar sus filtros y recibirán información de cómo reemplazarlo cuando sea necesario. Adicionalmente, las familias que colaboraron con el estudio y que no recibieron el filtro al inicio, se les entregará el filtro con la información necesaria de cómo usarlo y reemplazar las partes que requieran.**

Este proyecto tomará aproximadamente seis semanas, aunque podemos regresar luego para solicitar más información que nos sirva para determinar mayor información del uso a largo plazo. Su decisión de participar o no en esta prueba es autónoma, si en algún momento durante los ochos semanas usted decide que no desea continuar se puede retirar sin ningún inconveniente, excepto que debe devolver los filtros. Toda la información que nos suministre será, en lo posible, confidencial, los nombres de su familia no aparecerán en los reportes del estudio. Los filtros y las pruebas no tendrán ningún costo para usted; si no desea participar en este proyecto, pero desea aprenden más acerca de la relación entre la diarrea y la mala calidad del agua y que puede hacer para mejorarla, nos gustaría suministrarle alguna información y materiales educativos.

Participando en este proyecto usted y su familia se pueden beneficiar recibiendo el filtro al principio o final del estudio, el cual ayudará a mejorar la calidad del agua que bebe y la salud de su familia. Su participación puede ayudar a muchas comunidades porque cuando les mostremos que el filtro sirve para mejorar la calidad del agua, el sistema estará disponible para muchas otras comunidades y esto dará a ellos los mismos beneficios que ustedes han recibido. Su participación en este estudio no representa para usted ningún riesgo, salvo que para usted resulte incómodo tener las visitas de monitoreo. Si no le gusta alguna de las preguntas que le formulemos, no tiene que responderla.

Tiene alguna pregunta? Si durante el proyecto tienen preguntas sobre la prueba o sobre los derechos que usted tiene por participar en esta investigación, usted debe dirigirse a mi y con gusto le brindaré las aclaraciones que requiera. Le gustaría participar en el proyecto? Si su repuesta es Sí: Ahora le voy a leer una declaración y si está de acuerdo con esto, le pediré que firme este documento para confirmar su intención de participar.

ACUERDO PARA PARTICIPAR

La descripción del proyecto de investigación descrito arriba, fue leído para mi por el representante de la Escuela Londres de Higiene y Medicina Tropical. Lo que no entendí me fue explicado y las preguntas que tuve fueron respondidas. Voluntariamente estoy de acuerdo con participar en este proyecto.

Nombre de la persona que da el consentimiento:

Firma_______________________/ Fecha________________

Direccion____

Appendix VIII: Biographies

The following individuals assisted the team with the experiment:

Thomas Clasen (Milwaukee, WI USA): *Tom is a lecturer in Household Water Management at the London School of Hygeine and Tropical Medicine, LSHTM, and is owner of a non-profit organization called First Water. He previously practiced law and is now pursuing a PhD at LSHTM*.

Sophie Boisson (London, UK): *Sophie is an MSc candidate in Control of Infectious Diseases at LSHTM.*

Father Alex Busuttil (Arequipa, Peru): *Alex is a priest with the Sociedad Misionera de San Pablo and is Vicar of Social Programs for the Archdiocese of Arequipa, Peru. He was recently elected to be president of the rotary club in Arequipa. Alex has been in Peru for ten years and is originally from Malta.*

Ricardo Rojas (Lima, Peru): *An employee of the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS).*

Susan Murcott (Cambridge, MA, USA): *Susan is a research engineer at MIT and the motivating force of the team's endeavors.*

Robert Malies (Cambridge, UK and Cambridge, MA, USA): *Robert is pursuing a 4-year MEng program in the department of Engineering at Cambridge University and spent his 3rd year studying at MIT. He began conducting research for Susan Murcott in February of 2004.*

Amber Jaycocks (Cambridge, MA, USA): *Amber is an MIT undergraduate in the department of Civil and Environmental Engineering*.

Jennifer Lappin (Medford, MA, USA): *Jennifer is a MS candidate in Water Resource Engineering and Environmental Policy in the department of Civil and Environmental Engineering at Tufts University*.

Viviana Ruiz Longhi (Arequipa, Peru): *Viviana is a chemical engineering graduate with a BS degree from the University of Arequipa.*

Ana Gil (Lima, Peru): *Ana is the Principal Investigator at the Nutritional Investigations Institute (NII) in Lima, Peru. NII acted as co-sponsors of the First Water study.*

Clemente Vicente Yucra Mamani (Cerrito Buena Vista, Arequipa, Peru): *Clemente is the elected village president of CBV.*