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Slow-sand water filter: Design, implementation, accessibility and sustainability in developing countries

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Summary

The need for clean water has risen exponentially over the globe. Millions of people are affected daily by a lack of clean water, especially women and children, as much of their day is dedicated to collecting water. The global water crisis not only has severe medical implications, but social, political, and economic consequences as well. The Institute of Catholic Bioethics at Saint Joseph's University has recognized this, and has designed a slow-sand water filter that is accessible, cost-effective, and sustainable. Through the implementation of the Institute's slow-sand water filter and the utilization of microfinancing services, developing countries will not only have access to clean, drinkable water, but will also have the opportunity to break out of a devastating cycle of poverty.

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water filter • slow-sand • microfinancing • ethics • filtration • typhoid

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BACKGROUND

Clean water is an essential human right which has devastating medical, economic, and social consequences if unavailable. Across the globe more than 1.1 billion people, mostly in low and middle-income countries where the average national income is less than \$4,000 a year, lack access to safe water sources within a reasonable distance and quantity from their home [1]. Today, it is the vulnerable populations of these low and middle-income countries that are affected the most by the water crisis.

Now more than ever there is a need for clean water, as the need for water has outpaced the rate of the planet's population growth over the last century [2]. There are an estimated 400 million children in the world who do not have access to safe drinking water and over five million people die every year due to water-related diseases. Approximately 80% of deaths for children under the age of 5 occur because of water-related illness [3].

Research fellows in the Institute of Catholic Bioethics of Saint Joseph's University recognized this crisis and accepted the challenge to do something to improve the availability of clean water resources within low and middle-income countries. Since 2007, the fellows of the Institute of Catholic Bioethics have been working on the development of a cost-effective, accessible, and sustainable water filtration system to provide clean water for families in developing countries. To ensure sustainability and cost-effectiveness, microfinancing services will be utilized to construct and sell the filters. Microfinancing provides financial services to low-income clients who lack access to basic banking services such as loans, savings, and money transfer services as a result of a lack of collateral, steady employment, or a verifiable credit history.

Slow-sand water filters such as the model designed by the fellows of the Institute of Catholic Bioethics effectively reduce coliform bacteria, bacterial indicators for the quality of water, to safe limits for drinking:

No other single process can effect such an improvement in the physical, chemical, and bacteriological quality of surface waters [4].

Most slow-sand filters can remove 99% of bacteria, and some are even effective in removing some viruses (the Institute of Catholic Bioethics did not test the filter for removing viruses and parasites however). Through four months of testing, the slow-sand water filter developed by the fellows of the Institute of Catholic Bioethics has proven to reduce coliform bacteria by approximately 99% under ideal conditions.

Unsafe drinking water not only adversely affects the individual and the family, but society as a whole. Water is essential for life; therefore, it is one of the highest priorities in the lives of people who find themselves in situations in which clean water is unavailable. Finding drinking water becomes the central focus of daily life rather than education, employment, and development. The immediate need for water takes a higher priority than anything else and hinders further development, preventing developing countries from breaking out of a devastating cycle of poverty.

Slow-sand filters have been shown to not only improve public health, but also stimulate economic growth. The World

Health Organization (WHO) estimates that for every \$1 invested in clean water technology there will be returns of \$3–\$4, depending on the region and technology [5]. More than 200 million hours each day are spent by women and children collecting water from distant and often polluted sources [6]. Rather than spending their day in the classroom, children are spending their day collecting water. Without education, progress is very difficult for a developing country.

In addition to the medical and economic implications of the water crisis, there are also serious ethical concerns. The United Nations recently proposed *Article 31* [7], which is an amendment to the 30 articles of the *Universal Declaration of Human Rights* that describes water as a basic human right. The *Universal Declaration of Human Rights* was drafted shortly after World War II in order to prevent the tragedies and violations of human rights that had occurred in the years before from ever occurring again. Although the United Nations has declared access to clean water a fundamental human right, it has still not been amended to the *Universal Declaration of Human Rights*. Article 31 states, "everyone has the right to clean and accessible water, adequate for the health and well-being of the individual and the family, and no one shall be deprived of such access or quality of water due to individual economic circumstance [7]." Since water is a human right, developed countries should be obliged to respect and foster this right for those who do not have clean water resources.

Human rights are political norms that protect people from severe legal, political and social abuses [8]. There are generally six types of recognized rights, and among these, the right to water would be described as a "social right". However, human rights also exist independently of these legal, political, and social constructs by being linked to human morality. Humanity and morality are inextricably linked through facets of reasons and values. If human life is to be valued specifically then human life must also be valued universally, or as put forth in the *United Nation's Universal Declaration of Human Rights*, "All human beings are born free and equal in dignity and rights [9]. Therefore, access to and availability of clean water is a human right, considering that water is necessary for maintaining human life, thereby upholding the value of human life that morality has dictated.

The purpose of this article is eightfold: first, to give a detailed history of the project since 2007; second, to explore the medical implications of unclear water; third, to describe how slow-sand filtration effectively reduces disease-causing bacteria in contaminated water; fourth, to present an overview of the design, construction, and cost of the proposed filter; fifth, to present a description of how the filter should be maintained and implemented in a developing country; sixth, to present an explanation of the testing program that has been carried out to evaluate the filter's effectiveness; seventh, to show how the microfinancing model and Non-Governmental Organizations used in conjunction with the filters can spur economic development; and eighth, to give an ethical analysis of this project.

HISTORY OF PROJECT

For over five years, the fellows of the Institute of Catholic Bioethics have worked diligently in developing a water filter.

Although the water filter itself has undergone many changes since the project began in 2007, the criteria for the water filter remained the same; cost-effective, reliable, accessible, and sustainable. Over the years, changes were made to the filter if the students and faculty at the Institute did not feel that the filter adequately met any of these criteria.

The concept for the water filtration project came from three current and former undergraduate fellows in the Institute of Catholic Bioethics when they spent six weeks in Tanzania working at St. John's Parish medical clinic in Dar es Salaam (Parish Luhanga, Archdiocese of Dar Es Salaam). The group consisted of Stephen Szapor, who was a current fellow in the Institute, Justin Eisenman, a fourth year medical student at Philadelphia College of Osteopathic Medicine (PCOM), Luke Surry, a first year medical student at Georgetown University and Peter A. Clark, S.J., Ph.D, Director of the Institute of Catholic Bioethics. The group experienced firsthand a large number of patients, especially children, who not only had malaria but also suffered from typhoid fever as a result of the contaminated water in that particular area of Dar es Salaam. After seeing how dire the situation was, the group discussed the need for clean water with the parish's pastor, Father Emmanuel McChopa, SJ.

Father McChopa discussed the 2007 parish initiative entitled "Improving Water Supply and Sanitation" with the group. This plan addressed issues of sustainability, sanitation, degradation of water sources, and lack of public services. The parish initiative aimed to bring clean water and proper sanitation to all residents of the parish area, which would not only improve the health of the residents, but also reduce the workload, especially for women, as women spent most of the day collecting water. The group returned and saw an opportunity to put the mission of the Institute of Catholic Bioethics into practice.

The design group originally went through a number of different ideas for the filter. There were many significant changes and improvements over several different models, based on and including:

- Potters for Peace, Ceramic Water Purifier with colloidal silver,
- Water filter developed by Dr. Gary Michels, Associate Professor, Creighton University,
- Slow-sand water filter: copper pipe model, developed by the Institute of Catholic Bioethics,
- Slow-sand water filter: PVC pipe model with colloidal silver, developed by the Institute of Catholic Bioethics,
- Slow-sand water filter: plastic bucket model, developed by the Institute of Catholic Bioethics.

The first design that was used as a model for the slow-sand filter was the *Ceramic Water Purifier* developed in 1981 by Dr. Fernando Mazariegos of the Central American Industrial Research Institute [10]. Although the Ceramic Water Purifiers were effective and inexpensive, the Ceramic Water Purifier was abandoned because the filters were fragile and therefore not sustainable. This particular model was also abandoned because it was not accessible, as the ceramic filter requires a large press to manufacture. These filters are made of terra-cotta clay, sawdust, or other combustibles and then treated with colloidal silver for its anti-microbial properties [10]. Although this model was not used,

some of the general ideas from this particular model were utilized years later.

Another design that was examined by the fellows of the Institute of Catholic Bioethics came from Creighton University. This particular design at the time was implemented in the Dominican Republic. The design group had seen the filters in the Dominican Republic and had the opportunity to talk with Dr. Gary Michels of the Chemistry Department at Creighton University. However, after further examination this model was also abandoned because of sustainability and accessibility issues similar to the problems found with the Ceramic Water Purifier.

In the fall of 2008 the design group of the Institute used the ideas from the previous water filtration systems in addition to research of a water filtration system that had originated in the Philadelphia area in the early 19th century [11] to introduce a new approach to the Institute's design of a household filtration system. This system, known as a "slow-sand filtration system" had been utilized in Philadelphia and seemed to be a viable option for water purification.

The fellows of the Institute developed a slow-sand water filter from a copper pipe supported by a metal stand. The copper pipe was approximately two feet in length, two inches in diameter, and was filled with sand and gravel. Copper was chosen because there was a major concern that the water filter could harbor bacteria within the walls, and exposure of microbes to copper surfaces rapidly destroys bacterial cells within minutes [12].

The copper model was abandoned later that year because of a few concerns, mainly the reduced efficacy of copper as an anti-microbial agent when wet, the high cost, the high potentiality for theft, and limited availability of the copper piping in developing countries. The flow rate of the filter was also insufficient, limiting the amount of water for a family to use throughout the day.

A few months later, the copper pipe was replaced by a polyvinyl chloride pipe (PVC), which has similar properties to the copper piping in that it does not harbor bacteria. PVC piping was a good alternative to copper because it was less expensive and therefore less vulnerable to theft. PVC piping is also quite accessible in many developing countries, and was advantageous because it allowed for different size diameter filters to be designed and constructed.

Using these new ideas that PVC piping offered, two models were designed and constructed. The first filter that was developed was a PVC pipe model that measured 36" in length and a 6" diameter that sat over a 5 gallon collection bucket (Figure 1). The collection bucket held the filtered water and was controlled through a plastic spigot which was drilled into the side and connected to the sides using plumber's tape and rubber O-rings.

The group used the Potters for Peace' *Ceramic Water Purifier* as inspiration for the second model. Instead of using PVC piping, the group used two buckets superimposed on one another, much like the clay-pressed bucket that sat inside a plastic bucket in the Ceramic Water Purifier model. The bottom bucket acted as a collection bucket controlled by

Figure 1. First PVC model designed and constructed out of 6" PVC pipe over five gallon bucket (December 2010).

a small plastic spigot, and the upper bucket sat above with sand and gravel. Holes drilled in the first bucket allowed water to pass through.

Shortly after construction of the 36" PVC pipe model, it was decided that this model was far too cumbersome and difficult to construct. This particular model was not consistent with the criteria that the group established years before, especially accessibility. The two-bucket model was much more efficient to operate, maintain, and construct. In January 2011, the 36" PVC model was abandoned, and the group moved all of their efforts to the two-bucket model.

More improvements to the bucket model were made in the spring of 2011, after six of the students working on the water filtration project had the opportunity to see first-hand the need for clean water during a trip to Guatemala as part of the *Just Healthcare in Developing Nations* course. In Guatemala, the students saw a similar water filtration system to the two-bucket model that they had already produced (Figure 2) and upon their return to the University improved the current model by changing the size of the bucket from a five gallon bucket to a six gallon bucket (Figure 3). Although the water filter design underwent various changes over the last four years, the water filtration system's purpose has remained the same: to provide clean water sources to a level that is free of microbial agents or acceptable to drink.

MEDICAL ISSUES

Water-borne pathogens are associated with diarrhea and a host of other gastrointestinal problems. The most prevalent water-borne diseases in developing countries are bacterial diarrhea, Hepatitis A, Typhoid fever, and *Schistosomiasis*, which is a parasitic disease caused by trematodes [1]. Other

Figure 2. Water filter used in Rural Guatemala used to provide clean water for a family (January 2011).

Figure 3. The most current filter produced by the Institute. This is the model that has been tested since the summer of 2011.

examples of water-borne pathogens include parasites, bacteria (*Salmonella*, *Escherichia coli*, *Vibrio cholera*), and viral pathogens.

Of particular importance to the Institute's water filtration project is the ability of the filter to reduce the rates of typhoid fever infection, which is caused by the ingestion of food or water sources contaminated with the bacteria *Salmonella* Typhi. There are an estimated 22 million cases of typhoid fever reported annually worldwide, affecting mostly young children and young adults between the ages of 5-19 years old [13]. Once food or water contaminated with *Salmonella* Typhi is ingested by the individual, the bacteria enters the body through the gastrointestinal tract and is carried to the bloodstream, where it can travel to the lymph nodes, gallbladder, liver, spleen, and other parts of the body. In some cases, individuals remain carriers even after symptoms disappear through medicinal intervention and continue to release the bacteria in their stools, spreading the disease.

The most common symptoms associated with typhoid fever include a sustained fever as high as 103 to 104 degrees Fahrenheit, weakness, stomach pains, headache, and loss of appetite. Untreated typhoid fever results in a very rapid medical decline of the state of the patient, generally within a four week timeframe. There are also some serious

complications that can arise from individuals affected by typhoid fever. The most common complication resulting from lack of medical treatment, as seen mostly in developing nations, is intestinal hemorrhage caused by intestinal perforation which can lead to anemia [14]. The combination of massive internal bleeding, dehydration, and lack of medical treatment can ultimately be fatal.

Typhoid fever has almost become non-existent in developed countries with the advent of modern sanitation and public health measures. Unfortunately, many developing countries do not have the sewage and sanitation, or the vaccination programs that are largely responsible for preventing typhoid fever. Developed countries often treat typhoid fever by administering fluids and electrolytes intravenously, in addition to antibiotic treatments for advanced stages of the disease. However, these options are not always available in rural and developing countries.

For an individual to develop a water-borne illness, an “infectious dose” of the pathogen must be ingested. There is a certain threshold of bacteria or pathogen that can be tolerated before the individual becomes infected. Water filtration devices, among them slow-sand water filters, may not completely remove all of the infection-causing bacteria in the contaminated water, but they often will remove enough pathogens to a level that is safe enough to drink and will be tolerated. If a slow-sand water filter reduces the number of pathogens but the water is still not contaminant free, the individuals drinking from the water filter will nevertheless need to drink more of the contaminated water to ingest the infectious dose [4].

Although a water purification device would help decrease the rates of typhoid fever infection, a water filter would only be part of a comprehensive public health strategy to help reduce illness and mortality from water-borne diseases. Other public health strategies include adequate water treatment, waste disposal, sewage systems, and protection of food and water supplies from contamination.

SLOW-SAND FILTRATION

Slow-sand water filtration is not a new concept; it has been used for hundreds of years for its ability to reduce water-borne illnesses [15]. It is estimated that there are over 500,000 people in developing countries currently using slow-sand filters [16]. Slow-sand water filters have many advantages: they do not require chemicals, are easily maintained, and are relatively inexpensive.

Slow-sand water filtration works through two mechanisms: mechanically filtering bacteria through the grains of sand, and the adsorption of bacteria to a biofilm layer known as the *schmutzedecke*, a German word for “dirty blanket” [15]. The *schmutzedecke* layer forms among the top few centimeters of sand in the water filter.

The first method of filtration for slow-sand water filters is a simple mechanical filtration. A particle of fine sand is roughly 60 micrometers, and the distance between grains of very fine sand is even smaller. Bacteria are often slightly larger than the spaces between sand and soil particles. For example, *Salmonella typhi* is rod-shaped and is only a few micrometers in length and diameter. As water is passed through the

slow-sand filter, some of the bacteria will be trapped within the spaces between the sand, and water will continue to pass through. Trapped bacteria will then contribute to the biofilm layer, the *schmutzedecke*.

The most important aspect of a slow-sand water filter is the biofilm layer. Mechanically straining the microorganisms in the sand is not nearly as effective as the filtering processes that occur in the *schmutzedecke*, which consists of bacteria, algae, and other single and multiple cell organisms. Initial filtration efficiency without a *schmutzedecke* layer is roughly 60% [15]. As more microorganisms pass through the *schmutzedecke*, new microorganisms adhere to the previously deposited biological matter built up in the top layers of the sand. The major biological processes that take place in the top layers of the filter include “predation, scavenging, natural death/inactivation and metabolic breakdown” [17]. These processes are expected to enhance over time, as “maturity of the sand bed is a critical factor influencing particle and microorganism removals” [17]. An effective biofilm layer takes between one to three weeks develop [4].

Most of the filtration in a slow-sand filter occurs on the filter surface, almost entirely in the biofilm layer. However the depth of the filter is still also important to consider. A filter with a greater depth allows the filter to be scraped and cleaned before more sand is needed [15].

There are two other variables that can alter the effectiveness of a slow-sand water filter: the size of the sand particles, and the uniformity of the sand particles. The uniformity of the sand particles is represented by the uniformity coefficient, which is just as important as the size of the sand grains. The uniformity coefficient of sand is defined as a ratio: the size at which 60 percent (by weight) of a sand sample passes through a sieve, divided by the size at which 10 percent of the same sample (by weight) passes through a sieve. A uniformity coefficient of 1 indicates all the particles are the same size. As the number increases in size, the differentiation becomes greater and the quality of the sand becomes less desirable for use in a slow-sand filter [18]. The sand particles must be very similar in size in order to maximize the effectiveness of the filter. If there is great variability in the sizes in the grains of sand, the smaller sand particles will fill in the spaces between the larger particles, which could coincidentally clog the filter.

The size of the sand grain is also important to consider, especially since grain size affects the speed of filtration, the maintenance of the filter, and the effectiveness as well. Larger grain sizes are more desirable, as water can be filtered faster through coarser sand. Very fine grains of sand will have smaller sizes in between grains and provide more effective filtration, but would coincidentally have very slow water movement and a greater chance of clogging [19]. Research has proven that the most effective size for sand filtration is between 0.35 mm and 0.15 mm, and it is best if the uniformity coefficient is less than 2 [20]. However grain size does not apply to the level of gravel at the bottom of the filter, which is used for support, and is typically only a few inches in depth.

DESIGN, CONSTRUCTION, AND COST OF FILTER

The following description of the filter’s design and construction will begin with the outside and top of the apparatus and

Table 1. Comparison of the cost of production of the filters in U.S. Dollars and Kenyan Schillings. Prices in Kenyan Schillings are from the Dagoretti Market in Nairobi, Kenya. It is recommended that households build two filters however, as the full cleaning process takes 10–20 days.

	Cost in U.S. dollars (Philadelphia PA)-\$	Cost in Kenyan Schillings (KES)
Bag of fine sand (50 lbs)	3.66	350
Two Buckets	3.00 (×2)	(2× for 2 buckets) 350
Spigot	6.00	170
Gravel (pebbles found outside)	0.00	0
Matrix of mesh and cheesecloth	1.10	90
Total (\$)	16.76	1,310 (approximately \$12 US)

continue through to the bottom in the same direction as the flow of water. Two buckets placed one inside the other make up the frame of the filter. The two buckets are identical and measure 18" in height and 11.5" in diameter. The inside, upper bucket holds approximately 24" of sand, and holds 4 Liters of water at a time without overflowing. Beneath the sand there are 2" of gravel, which is used for support and to provide a barrier between the fine sand and a matrix of meshing and cheesecloth. This cheesecloth matrix lies beneath the gravel and acts as the final component of the filtration process. Once water passes through the matrix, it filters through holes that are drilled into the base of the inside bucket. There are about eleven evenly spaced holes that each measure 25" in diameter. Water passes through the holes and into the second bucket which acts as a reservoir for the clean water. Potable water will remain in the reservoir until a plastic spigot attached to the outer side of the bucket is opened, releasing the water. The reservoir below holds approximately 4 liters of water and when full, it stops the filtration process until water is released at the spigot, thus clearing room in the reservoir for new water to enter.

In addition to ensuring that the filter is "effective", it is just as important to ensure that the filter is "cost effective". See Table 1 for a list of the raw materials used in building the filter, along with the associated cost for each piece in both the United States (Philadelphia PA) and Nairobi, Kenya (Dagoretti Market). The prices were provided by individuals who work and shop in Dagoretti market – however, prices do vary from seller to seller depending on the relationship of the customer and the seller. When examining the cost of the filter it is important to note that the gross national income per capita in Kenya is \$1610 US Dollars [21]. It is also important to note that the fellows of the Institute of Catholic Bioethics recommend that two filters are purchased because of the length of time it takes for a full cleaning of the filter. A filter built in Kenya will not necessarily be constructed with a cordless drill as used in Philadelphia when constructing the filter, but will instead need an additional hand-powered drill for 100 schillings. Prices at the Dagoretti market are also conservative estimates, as prices could perhaps be lowered if bargained for in the native language.

FILTER MAINTENANCE AND IMPLEMENTATION

There are important aspects of maintenance and implementation that must be addressed to ensure that the filters are

successful. Although the fellows of the Institute of Catholic Bioethics have researched several aspects of filter maintenance and implementation, none have yet been tested by the Institute. Once tested, clear guidelines will be offered to the community in which they are implemented. Before any sort of filter implementation program is begins, all aspects of filter maintenance will be personally tested by the fellows of Institute, as the safety of those who will be using the filters is the highest priority. A serious issue to consider is the effectiveness of the filters in-country compared to their effectiveness in a laboratory setting, where almost all variables are completely controlled:

The big question however is: how do these filters perform under real life conditions; out in the bush, in the huts and houses of rural Africans, years after the experts have left? Performance measured under controlled circumstances in a laboratory, or in the field relatively soon after a filter has been commissioned will only prove the potential of the technology. How the filters continue to function when used and maintained (perhaps incorrectly) under controlled conditions is what determines the long-term sustainability and appropriateness [4].

Social acceptance is a critical aspect of successful water filter implementation as well. In order for social acceptance, there must first be trust between the group implementing the filter and the group accepting the filter. Members of the Institute of Catholic Bioethics will work closely with the Global Alliance for Africa (GAA) to ensure this. The GAA provides micro-financing services to help strengthen local economies and provide support for orphans affected by HIV and will partner with local non-profits and institutions to produce and sell the filters (see *Microfinancing* section for more detail). If a slow-sand water filter is not well maintained, the effectiveness will be compromised. Education on proper maintenance and risk factors is one of the most important aspects of implementation, keeping the filters as effective as possible.

Research has also suggested that in order to maintain a properly working filter, a constant flow of water must be running through the filter. This is indicated by the need for a water reservoir above the water filter, which will also provide a pressure head for the water to be pushed through the filter. Providing a steady flow of water provides oxygen and nutrients to the organisms of the biofilm layer. If the water remains stagnant, and new contaminated water is not frequently poured through the filter, the biofilm layer will begin to die and the effectiveness of the filter will be reduced dramatically [4]. The biofilm layer is an aerobic ecosystem, and oxygen

is critical for its survival [15]. Oxygen permeates the body of water that stands above the filter, and is delivered through diffusion to the organisms that live in the Schmutzedecke layer [4]. Essentially, a standing body of water of appropriate depth above the filter in the top reservoir is a must to maintain adequate filtration using the schmutzedecke layer.

Standing water is a necessary component of the slow-sand water filters, but it can also pose some serious issues, especially in countries that have been devastated by Malaria. It is suggested that a mosquito net be placed above the top of the filter, or a plastic lid. This will prevent the spread of diseases associated with stagnant water exposed to the air for prolonged periods of time.

It is suggested that the least contaminated water possible be used in these filters, because the filters are only effective for certain levels of bacteria, and using less-contaminated influent water will create safer drinking water. Slow-sand filters can handle no more than contamination levels of 800 CFU/100 mL. However this brings up a very difficult issue—how will those who are affected by issues of unsafe drinking water know which sources of water are the least contaminated? Testing water sources using inexpensive field kits would be an important aspect of filter implementation.

Another essential aspect of filter maintenance is cleaning the filter, although a “dirtier” filter actually produces water that is less contaminated than a filter that is recently cleaned [4]. Flow rate and filtration are inversely related: the slower the flow rate, the longer the water remains in the filter, the more time it has to come in contact with the biofilm layer. Although the flow rate may be reduced drastically as the filter remains uncleaned or unchanged, it is in fact producing water of better quality [4]. Slow-sand filters vary in which how often they need to be cleaned. It can be weeks or months in between cleanings, depending on how frequently they are used and how contaminated the influent water is. When the flow rate has slowed down so much that it does not adequately meet the needs of the family or community, it is recommended that the filter be cleaned.

As the filters approach this point, proper cleaning technique should be used. The owners of the filter will fill the top bucket almost to the top with water, and then “swirl” their hands around the standing water at least five times until the water becomes cloudy as a result of mixing with the surface layer containing the biofilm layer of the sand with the water. The contaminated water is then scooped out with a smaller bucket until almost all of the water has been removed from the filter. The contaminated water and sand should be dried completely to reduce the bacterial content to the minimum possible, as most bacteria are not resistant to desiccation and will be killed in the process. If drying to completeness is not possible, the waste should be buried. Testing of the safety of this cleaning method and method of disposal is a must before implementation of the filters.

The cleaning process is repeated until the flow rate has returned to what it was when it was a newly constructed filter. Operators of the filter must be aware that the biofilm layer takes approximately 10–20 days to form, and therefore water must be run to waste for two to three weeks before the filter is used again [4]. Filters that are freshly cleaned are

not nearly as effective once the biofilm layer has been temporarily destroyed. With this in mind, it would be beneficial for a home to have two filters that could be cycled. It is important to note that although sufficient time must be allowed for the filter to form a biofilm layer, the same filter can “recover” and form a biofilm layer much quicker than a newly constructed filter with fresh sand [15].

Slow-sand water filters should be installed in a location that is protected from damaging sunlight, wind, rain, animals, and children, preferably inside the home on level ground. Filters should be installed in an area where there is room to move large pails and buckets of water, so that water can easily be poured into the filter from above. The spigot or spout of the filter may be cleaned with an extremely diluted bleach solution of 1: 100 and a clean towel or rag. However many people in developing countries may not have access to bleach, bringing up another issue of sustainability. The price of bleach is another financial cost incurred by the filter as well.

EXPERIMENTATION AND TESTING

Testing of the slow-sand filters by the Institute of Catholic Bioethics is a work in progress, and is not near completion yet. The testing by the Institute is not a real indication of what actual conditions may be like where the filters may be implemented, as it involved only spiking deionized water with *Escherichia coli*. Contaminated water found in developing countries will have many other contents including ions, organic matter, and particulate matter, which may disrupt and adhere to a biofilm layer much differently than the influent water that the fellows of the Institute used.

There are many different techniques available to analyze water samples in order to estimate the coliform density. For this experiment, the Multiple Tube Fermentation (MTF) technique was followed, which estimates coliform density as Most Probable Number (MPN). By using MTF, it is possible to not only determine the presence of coliforms in a sample but also quantify the coliform level. The MTF consists of three phases: a presumptive test, a confirmed test, and a completed test. Although the MTF techniques includes these three phases, only the presumptive phase was necessary to analyze the influent and effluent water as the contamination of the water was being induced through the addition of *Escherichia coli*.

To perform the MTF test, different samples of bacterial concentrations were placed into standard test tubes lauryl tryptose and an inverted Durham tubes. The test tubes were incubated at 35°C for a 48-hour period, and growth and gas production were monitored in the inverted tubes after 24 hours and 48 hours. Following observation of the number of tubes that presented growth and gas production, an MPN table was consulted to estimate the total number of coliforms in the original sample. The filter’s efficiency was then calculated.

The MTF technique assumes the organisms are randomly and evenly distributed throughout the sample, exist as single entities, and that the growth medium, temperature, and incubation conditions have been selected to allow even a single viable cell in an inoculum to produce detectable growth. The MTF technique was conducted following the general

Table 2. MPN Index and 95% confidence limits for various combinations of positive tubes in a 3 tube dilution series using inoculum quantities of 0.1, 0.01 and 0.001 g (ml).

Combination of MPN Index 95% Confidence Limits	Positives per g (ml)	Lower	Upper
0-0-0	<3.0	–	9.5
0-0-1	3.0	0.15	9.6
0-1-0	3.0	0.15	11.
0-1-1	6.1	1.2	18.
0-2-0	6.2	1.2	18.
0-3-0	9.4	3.6	38.
1-0-0	3.6	0.17	18.
1-0-1	7.2	1.3	18.
1-0-2	11	3.6	38.
1-1-0	7.4	1.3	20.
1-1-1	11	3.6	38.
1-2-0	11	3.6	42.
1-2-1	15	4.5	42.
1-3-0	16	4.5	42.
2-0-0	9.2	1.4	38.
2-0-1	14	3.6	42.
2-0-2	20	4.5	42.
2-1-0	15	3.7	42.
2-1-1	20	4.5	42.
2-1-2	27	8.7	94.

Combination of MPN Index 95% Confidence Limits	Positives per g (ml)	Lower	Upper
2-2-0	21	4.5	42.
2-2-1	28	8.7	94.
2-2-2	35	8.7	94.
2-3-0	29	8.7	94.
2-3-1	36	8.7	94.
3-0-0	23	4.6	94.
3-0-1	38	8.7	110.
3-0-2	64	17.	180.
3-1-0	43	9.0	180.
3-1-1	75	17.	200.
3-1-2	120	37.	420.
3-1-3	160	40.	420.
3-2-0	93	18.	420.
3-2-1	150	37.	420.
3-2-2	210	40.	430.
3-2-3	290	90.	1000.
3-3-0	240	42.	1000.
3-3-1	460	90.	2000.
3-3-2	1100	180.	4100.
3-3-3	>1100	420.	–

United States Department of Agriculture, "Most Probable Number Procedure and Tables", 2008.

procedure by the "Standards Methods for the Examination of Water and Wastewater" [22] using Lauryl Tryptose broth as the growth medium. Tubes showing growth and gas production within 48 hours were considered positive.

The overall procedure for one filter test is as follows: *E. coli* colonies were grown on TSA (trypticase soy agar) plate. Individual *E. coli* colonies were placed in a nutrient broth culture and grown overnight. To obtain an estimate of the culture density, the optical density (OD) was measured using a UV-VIS (ultraviolet-visible) spectrophotometer at a wavelength of 595 nm. The culture was diluted to an optical density of 0.1 with sterile 0.85% saline solution.

By adding 1 mL of a 10^{-5} dilution of the prepared cell suspension into four liters of water, a sample of influent water of approximately 500 coliforms/100 mL was produced. The four liters of contaminated water were poured into the filter and eventually collected after the water filters through the sand and ended up in the collection reservoir (the "effluent" water).

The cell suspension used to spike the influent and the effluent was tested for total coliforms using the MTF technique described above to estimate the actual level of contamination of the influent water and the percent removal provided by the filter. See Table 2 for the MPN index used to estimate coliform levels, and see Table 3 for the experimental procedure followed by the fellows of the Institute of Catholic Bioethics.

Two filters were tested during the months of October and November to obtain more data for the filters and also to simulate the use of two household slow-sand filters at the same time (see Table 4 for results). The sand in the first filter was changed on November 14, 2011 since that sand had not been changed since April 2011. The second filter was assembled in the fall of 2011, so there was no need to change the sand. Only one filter was tested after November 14th 2011 because the plastic spigot broke off the second filter, and the filter began leaking. The plastic spigot is certainly a cause for concern of sustainability, but the price of a metal spigot could not be justified.

Table 3. Experimental procedure.**Materials**

1. 18 tubes of Lauryl Tryptose
2. 10 micro-centrifuge tubes with 900 uL of saline
3. Additional saline and sterile tubes
4. 1 tube of nutrient broth to inoculate *E. coli*
5. Pipette tips
6. 4 liters of distilled water

Influent Water Procedure:**Monthly:**

1. Bacteria must be streaked on nutrient-rich agar plate and incubated overnight to develop colony growth
2. Plate of bacteria will then be transferred to refrigerator for storage (Approximate storage duration of one month is expected)

Daily:

1. A small amount of bacteria must be obtained on the inoculating loop and passed into nutrient broth
2. Test tube must be placed in bacteria shaker for overnight growth
3. The following day, the Optical Density (OD) of the tube must be measured through UV Spectrophotometry. **(Put 1 mL of bacterial sample and blank into cuvettes)**
 - a. Use distilled water as blank
 - b. Set wavelength to 595 nm
 - c. Blank instrument and measure OD (absorbance)
4. Based on absorbance measurement, dilute sample to an OD of 0.1

VORTEX MICROCENTRIFUGE TUBES PRIOR TO PREPARATION OF EACH DILUTION

- a. Depending on OD reading, dilute the sample to obtain an OD of 0.1. Use this cell suspension as 10^0 to prepare a dilution series as follows. (I believe it is unnecessary to write all steps to j, it would be enough to say: prepare a 10-fold dilution series up to 10^{-9} .)
 - b. Add 100 uL + 900 uL saline to prepare 10^{-1} dilution
 - c. Add 100 uL + 900 uL saline of (b) to prepare 10^{-2} dilution
 - d. Add 100 uL + 900 uL saline of (c) to prepare 10^{-3} dilution
 - e. Add 100 uL + 900 uL saline of (d) to prepare 10^{-4} dilution
 - f. Add 100 uL + 900 uL saline of (e) to prepare 10^{-5} dilution
 - g. Add 100 uL + 900 uL saline of (f) to prepare 10^{-6} dilution
 - h. Add 100 uL + 900 uL saline of (g) to prepare 10^{-7} dilution
 - i. Add 100 uL + 900 uL saline of (h) to prepare 10^{-8} dilution
 - j. Add 100 uL + 900 uL saline of (i) to prepare 10^{-9} dilution
5. Begin Multiple Tube Fermentation set up in triplicate, using 1 ml of incula per tubes, and 10^{-7} to 10^{-8} dilutions from the dilution series
 6. Add 1 mL of 4(f) to 4 liters of distilled water, yielding approximately 500 FC / 100 mL

Effluent Water Procedure:

1. Run Multiple Tube Fermentation test to enumerate total coliform level of effluent water by preparing a 10-fold dilution series to 10^{-2} , and conduct the MTF test in triplicate using 1 ml of inocula from the three dilutions in the series

A very effective filter has a removal rate of approximately 98%, which was the removal rate goal for the fellows of the Institute. The filters exhibited a removal rate below 98% during the first 16 L of influent water. The percent removal was satisfactory for 20–32 L of influent water; the removal rate fell drastically below the recommended percentage of removal after the addition of the 36th L of influent water. After sand in the first filter was replaced, the removal rate fell below the recommended percentage removal during the first 12 liters of influent water passed through the filter, but the percent removal was sufficient for the next 24 liters of water indicating that a proper biofilm layer had formed, allowing for removal rates of upwards of 99%.

MICROFINANCING AND ECONOMICS OF SLOW-SAND FILTRATION

Another goal of the Institute of Catholic Bioethics is to design a cost effective water filtration system that can be implemented in a developing country by way of an accessible and sustainable business model made possible through microfinancing. “Microcredit, or microfinance, is banking the

unbankables, bringing credit, savings and other essential financial services within the reach of millions of people who are too poor to be served by regular banks, in most cases because they are unable to offer sufficient collateral [23]. Globally, more than 3 billion people seek access to formal financial services such as loans, savings, and money transfers [24]. However, they are generally denied financial services based upon the inability of candidates to meet minimal qualifications such as evidence of collateral, steady employment, and a verifiable credit history in order to gain traditional credit. Proponents of microfinancing believe that access to these types of financial instruments will elevate the poor and the marginalized out of poverty. “When credit is extended directly to individuals and communities, self-sufficiency and thus the ability to access or purchase life-improving technological advancements- healthcare, farming techniques, digitized information- is not far behind. Access to technology is ultimately what separates good livelihoods from poor ones and microfinance is a proven method of bridging the gap [25].”

Highlighting microfinance as an instrument of socioeconomic development, the United Nations declared the year 2005

Table 4. Results from four months of testing. Two filters were operated during the fall of 2011. However one of the plastic spigots on the second filter broke, and the filter started leaking. Testing of filter two stopped after the spigot broke. On November 14th 2011, the fellows of the Institute changed the sand of the first filter, since the sand had not been changed since April 2011.

Test date	Total liters	Removal rate filter #1	Removal rate filter #2
10/3/11	4	96.74	99.67
10/10/11	8	97.86	95.82
10/11/11	12	—	95.82
10/11/11	16	90.00	99.68
10/24/11	20	98.21	99.88
10/25/11	24	99.04	98.21
10/28/11	28	97.98	99.94
11/1/11	32	99.67	99.85
11/2/11	36	90.00	99.92
11/16/11	4	99.67	—
11/ 17/11	8	95.81	—
11/21/11	12	95.81	—
11/29/11	16	99.67	—
12/5/11	20	99.87	—
12/6/11	24	98.20	—
2/13/12	28	99.93	—
2/15/12	32	99.85	—
2/ 16/12	36	99.92	—

as the *International Year of Microcredit* [26]. The proclamation called for “building inclusive financial sectors and strengthening the powerful, but often untapped, entrepreneurial spirit existing in communities around the world [26].” It is estimated today that between 70 and 750 million people across the globe utilize microfinancing [26]. The United Nations underscores the use of microfinance and microcredits as an instrument to improve the lives of those living in developing countries, especially in achieving one of the Millennium Development Goals, “To halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation.” It is estimated there is an economic loss of \$28.4 billion a year, or 5% of a country’s GDP, as a result of the lack of access to safe water and basic sanitation in Africa [27].

The lack of safe-drinking water creates cost burdens hindering economic development. Direct economic costs are incurred through the treatment needed after contracting water-borne diseases, along with the overall cost of ill-health on the nation’s economy. The costs of treatment for water-related diseases are burdens for families across the developing world, hindering education for children and work for adults. Moreover, ill health directly correlates to economic loss. There are lost economic contributions of the sick or prematurely deceased, as well as lower productivity resulting from sick and less educated workers. In addition, indirect costs may accrue from lost work and lower productivity of those who care for the afflicted.

By partnering with a non-governmental organization (NGO), the Institute of Catholic Bioethics aims to implement the proposed slow-sand water filter in a developing country. Characterized by their independence of government, NGOs are non-profits that are motivated to serve humanitarian, social, or cultural interests [28]. NGOs function by “providing goods and services not usually supplied by the state or the private sector; help the government to achieve its development objects by providing public information, education, communications campaigns, etc.; and organize citizens to voice their aspirations concerns, and alternatives for consideration by policy makers [29].”

The Institute will partner with the Global Alliance for Africa (GAA) out of Chicago, Illinois to create a pilot microenterprise program that will bring the filtration systems to a developing country in Africa. The GAA has a mission to partner with “local African NGOs, religious institutions, and community-based cooperatives to design and implement innovative, economic strengthening programs with the goal of enabling these communities and households to provide sustainable care and support for orphans and other vulnerable children affected by HIV/AIDS [30].” As of 2011, the GAA has provided over 20,000 loans, and funded over 4,500 small businesses such as weaving, rug making, fishing, and vegetable farming. Over 10,000 orphans have been provided care through these loans as well. The fundamental provision for the loan program entails that each

recipient of a loan must agree to provide care and support for orphans and vulnerable children affected with HIV/AIDS in Sub-Saharan Africa. The two separate initiatives: social services and economic development through micro-financing combine into a comprehensive model to benefit the poor and vulnerable.

Initial loans from the GAA range from US\$15.00 – US\$500.00 with an interest rate of 6.0% to 15.0%. The loan periods range from 6 months to 12 months depending on the amount of the loan [30]. Receiving the next loan amount is contingent upon repayment of the previous loan in full. Repayment dates are based upon each loan agreement wherein loans are repaid either monthly or bi-weekly.

By collaborating with the Institute, business members will learn how to properly build and maintain the filtration system. Through this model, the Institute of Catholic Bioethics will increase the proportion of people in Sub-Saharan Africa that have access to clean drinking-water while facilitating an opportunity for the poor to elevate themselves out of poverty through a sustainable business model.

ETHICAL ANALYSIS

“In 2000, the Millennium Development Goals were established to ‘halve, by 2015, the proportion of people living in extreme poverty and to halve the proportion of people who suffer from hunger and are unable to reach or afford safe drinking water.’ Yet the reality of universal access to water continues to be deferred, and the increasing corporate control of global water resources undermines steps made toward these goals[31].” Access to clean drinking water is a basic human right and is vital for our existence. It is estimated that approximately 884 million people across the developing world lack access to safe drinking water, while 2.6 billion lack basic sanitation [32]. On 30th September 2010 the UN Human Rights Council, responsible for mainstreaming human rights within the UN system, adopted by consensus a resolution affirming that water and sanitation are human rights [33]. Despite these developments, obtaining clean water is one of the most serious problems facing humanity today. “In many parts of the globe, obtaining water for everyday use requires an enormous diversion of time and effort. And beyond thirst and reduced productivity, the lack of clean water has very serious health consequences: Dirty water can transmit parasites, bacteria, and viruses and can inhibit sanitation, resulting in millions of cases of water-borne diseases each year, many deadly [34].” Failure to provide access to clean drinking water to all people is to deny them the basic dignity deserved as a human person. Availability of clean water is not only a medical, social, economic and political issue; it is also an ethical issue facing all of humanity. We believe that failure to provide access to clean drinking water violates the basic ethical principles of respect for persons, beneficence, nonmaleficence and justice.

Respect for persons incorporates two ethical convictions: first, that individuals should be treated as autonomous agents; and second, that persons with diminished autonomy are entitled to protection. The principle of respect for persons thus divides into two separate moral requirements: the requirement to acknowledge autonomy and the requirement to protect those with diminished autonomy [35]. Access to

clean drinking water is a fundamental human right implicitly supported by international law, declarations, and State practice. The term “right” is used as an entitlement, a genuine right under international law, where States have a duty to protect and promote those rights for an individual. The right to clean water is not an unlimited right. A right to water means access to adequate amounts of clean water for basic needs as drinking, sanitation and hygiene. This basic human right has serious implications for humanity. The WHO states that in Africa, people often focus on the number of deaths through wars and AIDS, but the number of people killed through water related illnesses is almost six times larger than wars [36]. Water issues in developing countries not only debilitate the people but society as a whole. If we believe that clean water is essential to human life and that billions of people in developing nations lack this essential good, then we, who have access to clean water, have an ethical responsibility to help correct this situation in order to respect and protect the rights of all people to clean water resources. Those in the world without access to clean drinking water are truly vulnerable and have a diminished autonomy. These individuals are not only entitled to protection but we who have access to clean drinking water, and at times take it for granted, have the ethical responsibility to help provide the means to attain this access. Some developed countries refuse to recognize clean water as a human right for fear they will be forced to share this resource with those in developing countries. Besides sharing water there are other ways that developed countries can protect the rights of the most vulnerable to clean water. These countries can change their water consumption behavior; they can condemn policies that treat water as a commodity governed by market forces or promote the privatization of public water utilities; they can work to reform sanitation, manufacturing and agricultural practices in all countries in order to protect and save the limited amounts of the world’s clean water [37], and they can provide technology and resources to filter contaminated water. On a smaller scale, individuals can also promote and protect the rights of the most vulnerable, who lack access to clean drinking water, by using their talents and abilities to seek a solution. The microfinanced slow-sand water filter, proposed by the fellows of the Institute of Catholic Bioethics at Saint Joseph’s University, is one solution to this problem. This may be a small step forward toward accomplishing a major goal, but it is at least a step forward. To stand by idly and do nothing to promote and protect this fundamental human right violates the basic dignity and respect of all persons.

Beneficence involves the obligation to prevent and remove harms and to promote the good of the person by minimizing possible harms and maximizing possible benefits. Beneficence includes *nonmaleficence*, which prohibits the infliction of harm, injury, or death upon others. In medical ethics this principle has been closely associated with the maxim *Primum non nocere*: Above all do no harm.

Allowing millions of people to be denied clean drinking water when said water could be provided violates the principle of beneficence because one is not promoting the good by maximizing benefits and minimizing harms and therefore not acting in the best interest of the most vulnerable people. It also violates the principle of nonmaleficence because it is causing harm, injury and even death to people. Clean

water is a basic human right that belongs to all people. It is not a commodity that can be hoarded by the developed countries or be privately owned. Governments have the responsibility to provide “sufficient, safe, accessible and affordable water without discrimination [38].” The problem is that many of these developing countries’ governments are semi-socialistic, so they view extra people as a burden; these governments often excuse their failure to extend state-owned services such as water, telephones, and electricity into peripheral urban areas with bureaucratic sleight-of-hand: denying the legal existence of people who live in these areas (e.g., “slum dwellers”) and refusing to recognize them as formal citizens [39]. If governments are unable or unwilling to provide this basic human right to people, then it is the responsibility of people in developed countries to devise ways to implement access to clean water. This can be done by placing political, social and economic pressure on appropriate governments, NGOs, international aid agencies, etc. to rectify this injustice. It can also be accomplished by encouraging universities, philanthropists and foundations to help design water filters and water treatments facilities that meet the basic needs of those without clean water. This is the foundation of the principle of beneficence, that is, maximizing benefits and minimizing harms. Failure to provide clean water to people in these intolerable situations comes very close to willfully inflicting harm, injury and even death. As human beings we have a moral obligation to do what is good for our fellow human beings. Compromising the basic ethical foundations upon which human rights stand is not only destructive for individuals and particular nations but for the world community as a whole. As human beings, we have an ethical responsibility to ensure that all people are provided their basic human rights. To accomplish this goal would entail advocating for the protection of global water resources, condemning government policies that treat water as a commodity, encouraging national and international policies that treat water as a valuable and finite resource, and providing adequate technical assistance in funding and implementing basic water and sanitation programs. To refuse to help not only fails the test of beneficence, but also may fail the test of nonmaleficence.

Finally, the principle of “*justice*” recognizes that each person should be treated fairly and equitably, and be given his or her due. Justice also pertains to distributive justice, which concerns the fair and equitable allocation of resources, benefits and burdens, according to a just standard. “It is estimated that the average United States citizen uses 180 gallons of water per day, while the average African uses between 10 and 20 gallons of water per day. The water we take for granted when we turn on our faucet is nothing like that of the average Africans – in Africa, most people have to walk hours to reach their water supply, and even then it is muddy and contaminated, something people from developed countries would be uneasy even swimming in [39].” Water is becoming a scarce natural resource and many in the developed world not only waste this valuable resource but plead ignorance that others are suffering as a result of their actions. Statistics show that 1.4 billion people lack clean drinking water in the world. By 2025 some 3 billion people will suffer from water shortages with over 80% of them living in developing countries. In developing countries, over 80% of all diseases can be traced back to the use of contaminated water [40]. If access to clean water is a basic human right, then

every member of the human race has the right to accessible, affordable water in a quantity and quality sufficient to life and basic economic activities [40]. Ignorance is not an excuse or a defense because it is a well-known fact that water is basic and essential to human existence. To plead ignorance violates the basis of being human. To allow some people in the world access to clean water and others to be subjected to contaminated water is an egregious violation of the principle of justice. Justice dictates that all people should be treated in a similar manner if at all possible. If clean water is available and accessible in developed countries as well as water filters and water purification systems that are cost-effective and sustainable, then failure to give the same access to those in developing nations violates the basic tenet of justice, that is, to treat all people fairly and equitably.

The slow-sand water filter designed and developed by the Fellows of the Institute of Catholic Bioethics at Saint Joseph’s University is not only effective and cost-efficient but through micro-financing it can also be accessible and sustainable. This project can serve as both a paradigm and a challenge to others in the developed world to help make access to clean water a reality for those living in developing. Failure to acknowledge the fact that billions of people in the world lack access to clean water and failure to provide solutions to this crucial life and death issue is ethically irresponsible and morally objectionable.

CONCLUSIONS

It is clear that the need for action is now. After years of research, and seeing the need firsthand in the Dominican Republic, Guatemala, Tanzania, and Kenya, the students and faculty at the Institute of Catholic Bioethics have come up with a strategy for not only improving clean water conditions, but also for helping elevate vulnerable and marginalized populations out of poverty. Although slow-sand filters alone are unlikely to solve the water crisis, they can certainly become part of a comprehensive public health policy to help restore the fundamental right to clean water to those who inherently deserve it. Through partnerships and investments in clean water initiatives, morbidity and mortality rates around the world can be reduced to achieve and surpass the United Nations Millennium Development Goal.

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