DEVELOPMENT AND IMPLEMENTATION OF THE *BRING YOUR OWN WATER TREATMENT SYSTEM* IN DENSE, RURAL, AND MOUNTAINOUS RWANDAN COMMUNITIES

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ABSTRACT

Over a billion people in the world lack access to safe drinking water[1]. While numerous technological, medical, and educational solutions have been implemented for the benefit of disadvantaged communities, there is no 'magic bullet'. Instead, development agencies must partner directly with these communities to address their public health needs through appropriate technology solutions, backed up by education and assessment.

The "Bring Your Own Water (BYOW) Treatment System" developed by the Engineers Without Borders-USA chapters at the University of Colorado at Boulder Chapter (EWB-CU) and the Johnson Space Center (EWB-JSC) is uniquely designed to address the water treatment requirements of two poor and overpopulated Rwandan communities. The BYOW system consists of a gravity-fed roughing filter, rapid sand filter, and solar-powered ultraviolet irradiation system. The BYOW system treats water collected in containers by local residents from any contaminated or suspect source. A key component is a self-filling tank for backwashing of the filter. The system treats water at a rate of approximately 10 liters per minute, and can provide up to 5,000 liters of treated water per day. The BYOW system performed successfully in long term tests in Houston, Texas. Activated sludge collected from a municipal sewage plant (over 70 NTU turbidity, 3,000 CFU/ml E. Coli) was introduced as input. The BYOW-treated effluent water was significantly cleaner (less than one NTU, 0-2 CFU/ml E. Coli).

A system installed in Muramba in 2006 was well accepted by users. A second iteration with significant improvements was installed in Mugonero in 2007. After two months of community testing, water quality results indicate that rainwater passed through the Mugonero BYOW system was reduced from up to 60 CFUs/ml coliform bacteria and up to 4.5 NTU turbidity to zero CFUs/ml and less than 2.25 NTU.

The BYOW system has the potential to be replicated around the world where communities have similar water treatment requirements, and no available treatment infrastructure or surplus energy resources.

IMPLICATIONS

Water-borne disease is a leading cause of illness in the developing world, contributing to the death of 15 million children every year, on average[1]. However, there has yet to be developed a catch-all technology that can successfully be implemented in most developing communities. The BYOW system developed by EWB-USA is a unique assembly of previously proven water-treatment technologies that directly addresses the specific constraints and requirements of poor, rural, mountainous, and densely populated Rwandan communities. This system and its subsequent iterations have the potential to directly address the biggest public health concern in many communities around the world. This project directly addresses several of the United Nations Millennium Development Goals (MDG), including *reducing child mortality, improving maternal health, combating disease, ensuring environmental sustainability, and developing a global partnership for development*[2].

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BACKGROUND

Engineers Without Borders-USA (EWB-USA), a non-profit humanitarian organization, was founded at the University of Colorado at Boulder in 2001 by Professor Bernard Amadei. It has since grown to 230 chapters across the United States, operating sustainable development projects in partnership with local communities in 41 countries. All-volunteer EWB-USA chapters at the University of Colorado at Boulder (EWB-CU), and the Johnson Space Center in Houston, Texas (EWB-JSC) have been working in Rwanda since 2003 on projects addressing public health challenges in rural communities.

Located in East Africa, Rwanda is a landlocked country that is slightly smaller than Maryland. With a fast-growing population of nearly nine million, it is the most densely populated country in Africa. Rwanda is very mountainous and poor with over 90 percent of the population working as subsistence farmers. Many families survive by cultivating less than one-third of an acre[3]. In 1994 Rwanda suffered a genocide, when, over the course of 100 days, as many as one million people were killed[4]. In the aftermath of the genocide, many public services have still not been rebuilt and continue to deteriorate. The new government currently lacks the resources to help many remote rural communities. In a private meeting with the BYOW implementation team, President Paul Kagame offered his support for EWB-USA efforts in Rwanda. "I wish to thank you for finding the time to come to our country. . . . As you have found out, we are not short of things to do. Everything here is about engineering; how to engineer reconstruction. We are always happy when people find time to come and help with things affecting people's daily lives."[5]

The communities of Mugonero and Muramba are located near Rwanda's western border with the Democratic Republic of the Congo. Neither are villages or towns in the traditional sense. Instead, they are dense sprawls of subsistence farms spread across hillsides, with little opportunity for water wells or protected sources. Both communities suffered intensely in the 1994 genocide, and subsequent incursions by the Interahamwe militia. When EWB-USA first visited Muramba in March 2004, community leaders introduced the team to their water provisioning challenges. Surface runoff water was harvested for community facilities by a deteriorating network of pipes and shallow collection boxes. This water was channeled through an inverted siphon to facilities on the opposite hillside. The pipes often leaked or broke, and during the dry season there was not enough water for users. During the two annual rainy seasons, waterborne illness spiked due to contaminants being washed into the unprotected water sources.

To address these public health concerns through appropriate technology solutions, EWB-USA has returned to the communities five times since January 2005. Projects were identified, developed, implemented, and monitored in partnership with the Muramba community leaders. As well as the water treatment system which is the subject of this paper, these solutions included drip irrigation, solar-powered lighting and computing, biogas generators, and rainwater catchments.

Public Health Assessment

A public health assessment, conducted by CU-Boulder Chancellor Emeritus Richard Byyny from the University of Colorado at Denver Center for Global Health, concluded that severe poverty is the greatest barrier to improving public health in Muramba and Mugonero. Some residents stated that an average family has less than ten dollars cash per year to purchase soap, clothing and health care. Only about 650,000 of the nearly nine million Rwandans are members of the government-sponsored, prepaid cooperative health insurance program. Severe malnutrition is frequent. The diet is mostly beans, corn, sorghum, pineapple, bananas, and potatoes derived from subsistence farming. Common illnesses observed include chronic bronchitis, anemia, malaria and diarrhea. Diarrhea is a chronic, life-long condition for most people—starting in childhood. Acute diarrheal illnesses are frequent because of contaminated water and may be due to enteropathic ecoli, giardia, amoeba, and others. Most are neither diagnosed nor treated. However, district and teaching Hospitals have laboratory facilities and medications to treat some patients.

Providing clean water, cleaner air, energy sources, education, health care, infrastructure, and economic development can prevent many of the diseases observed in Muramba and Mugonero. The greatest needs are in appropriate engineering solutions, agriculture, public health, economic development, education, and infrastructure development.

The public health assessment concluded that the BYOW systems should have a direct positive impact on the health of these communities, as residents now have access to treated water, thereby reducing the likelihood of exposure to contaminated water causing diarrheal illnesses.

Water Quality Assessment

A comprehensive water quality assessment was conducted by EWB-USA in Muramba and Mugonero in January 2006. This study was followed up in June 2006. Study excerpts and summaries are presented here. Two sets of representative results are presented, one from the Muramba Clinic and the other from the Mugonero Orphanage. The January testing was done during the first of two annual transitions from wet to dry seasons, and included several days of testing immediately after a rainfall. Results may vary greatly during rain events when water runs across surface areas that are not regular channels. This can contribute to an increase in turbidity, bacteria counts, and generally decreased water quality.

The tests conducted included pH, conductivity and Total Dissolved Solids (TDS) measured with a Hach SensION 156. Turbidity, Nitrate, Nitrite and Hardness were tested with a Hach Colorimeter DR/890. Alkalinity was measured with Hach test strips, and Coliform Bacteria were measured with Coliscan Easygel tests, or 3M Petrifilm tests where noted.

The Mugonero Orphanage testing included rainwater stored in the residential dormitories, a water collection tank used by the local community as well as the Orphanage, and a water stream near the Orphanage that is currently being pumped up to a storage tank for distribution. This pumped source is of the poorest quality tested so far in Rwanda by EWB-USA, and EWB-USA has advised the community to avoid drinking this water. The source was first tested directly after a rainstorm, and then retested for bacteria a few days later. The retest results are presented in parentheses, and indicate the potential for rapidly changing water quality.

The Muramba Clinic testing results presented in Table 1 include water that was carried to the Clinic from nearby surface water sources. The Clinic has been using chemical treatments (likely a chlorine solution) for this water, but these treatments are shown by these results to be ineffective for bacterial reduction. Additionally, the Clinic is connected to the main Muramba water pipeline that operates only intermittently. In January 2006, the communal water supply was non-functional. By June 2006, the supply was reliable and of good quality, but as of March 2007, the water supply was once again non-functional and staff, patients, and local residents were resorting to surface water sources.

The results from these six test points in the two communities are presented in Table 1.

Most of the water quality parameters fell within reasonable ranges. The biggest concern is the bacterial counts found in most water samples taken. By extension, the turbidity parameter is important because higher turbidity measurements are associated with higher levels of disease-causing organisms attached to particulates such as viruses, parasites and some bacteria, which can cause nausea, cramps, diarrhea and headaches.

Total Coliforms are not as much as a concern in the developing world because most residents have a natural resistance to coliform bacteria. The prime concern is fecal contamination, tracked through the heat-resistant coliform bacteria, E. Coli[6]. Some sites showed no sign of E. Coli contamination, though most had fairly high counts of total coliforms. Both of the samples taken from the water transported to Muramba Clinic by residents did show E. Coli, indicating human and animal fecal contamination. Likewise, the Mugonero Orphanage samples showed very high E. Coli counts and total coliform counts. Figure 1 shows representative plate testing results for the Orphanage pumped water source, while Figure 2 shows a clean, non-impacted growth plate for comparison.

DESIGN

Water Treatment Requirements

The public health and water quality assessments indicated that the Muramba and Mugonero communities were in need of water treatment solutions. While rainwater catchment systems had been successfully

TABLE 1. Muramba and Mugonero, Rwanda water quality testing results. Shaded blocks show parameters exceeding standards.

	WHO Standard	Mugonero Orphanage house rainwater	Mugonero Orphanage community water collection tank	Orphanage Pumping Source	Muramba Clinic water without chemical treatments	Muramba Clinic water with chemical treatments	Clinic Tap
Test Date		1/12/2006	1/11/2006	1/12/2006	1/7/2006	1/6/2006	6/23/2006
pH	6.5 - 8.5	6.52	6.23	6.85	6.32	5.62	5.87
Temperature (Celsius)	—	—	20.1	—	21.5	22.7	22.6
Alkalinity (ppm CaCO3)	Target 150	—	—	—	20	80	—
TDS (mg/L)	None (EPA standard: 500)	20	41.8	37.7	60.3	54.6	25.6
Turbidity (FAU)	—	38	0	68	2	5	0
Nitrate (mg/L NO3-N)	Total N	2.5	3.7	1.7	2.7	3.4	3.3
Nitrite (mg/L MO2)	Total N	5	1	0	0	2	—
Total Hardness (mg CaCO3 /L)	1-150 soft, 150-200 target, 200+ hard	17.8	15.2	20.7	23.7	134	—
Conductivity (microS/cm)	~ 2 times the hardness	39.3	80	72.8	117.2	108.4	52
E. Coli (CFU/100 ml)	0	0	0	12,500 (2,200 retest)	500	800	0 (3M Petrifilm)
Total Coliforms (CFU/100 ml)	0	900	500	(15,000 retest)	30,000	20,000	1 (3M Petrifilm)

implemented by EWB-USA in Rwanda, the capacity was not sufficient to support the large communities. Furthermore, rainwater catchments are unprotected and would still require treatment. Therefore, treating the already available and collected surface water was deemed to be the appropriate solution.

The Muramba Clinic was chosen to be the site for the first water treatment implementation. To improve the quality of the drinking water consumed at the Clinic, the team chose to install an on-demand water treatment system that would treat water on a bucket-by-bucket basis. This type of system was chosen because it works independently of the water source. Nearly all drinking water consumed in rural Rwanda is transported in jerry cans or buckets from stream, community taps, or rainwater catchments. By installing a container-level treatment solution at the Muramba Clinic, all users have access to treated water, regardless of the original source. Likewise, the second implementation, a year later, was at the

FIGURE 1. Petrifilm bacteria testing results for the Orphanage Pumping Source.

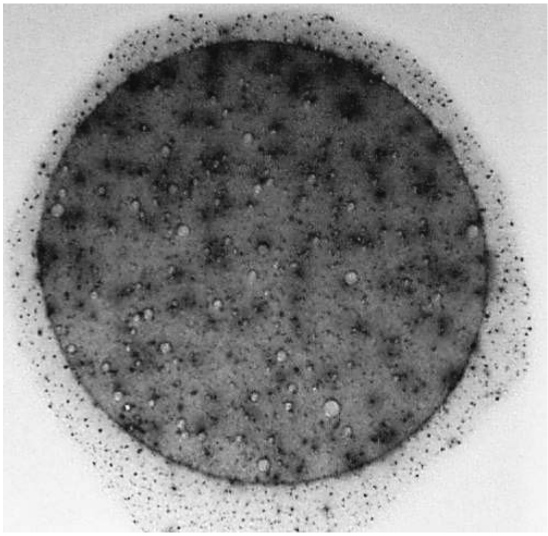
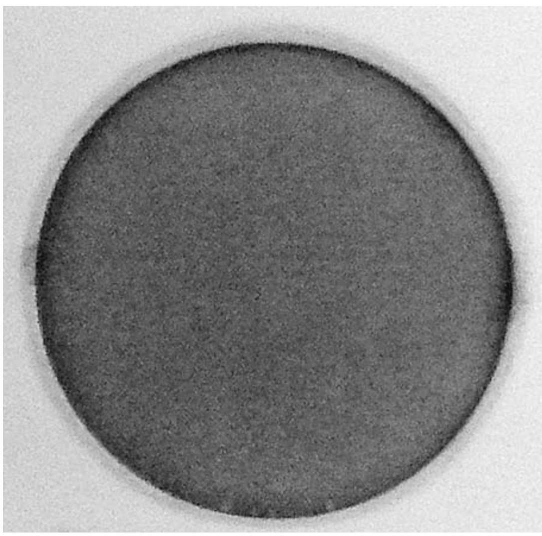


FIGURE 2. Clean growth plate.



Mugonero Orphanage where the children collect surface water, and now catchment rainwater.

These communities have unique water treatment requirements compared to many other developing communities. Firstly, the communities are very densely populated, with each family farming less than a third of an acre. Families live virtually atop one another. Communities and service areas are poorly delimited. Secondly, Rwanda's mountainous terrain makes wells generally impractical. Thirdly, the residents are extremely poor, and have very little disposable income or time for water treatment. This is in contrast to many other developing communities were there is at least a nominal available investment of time and money from an average resident.

The primary objective of this work was to address microbial contamination of drinking water for the Muramba Clinic and the Mugonero Orphanage. The basic requirements suggested a system with a simple yet robust design that could provide at least 5,000 liters of drinking water per day while minimizing capital and maintenance costs in order to maximize sustainability. The requirements derived by the team for the water treatment system are detailed in Table 2.

Water Treatment Trade Study

There are some available technologies that are capable of decontaminating water in developing communities such as Muramba and Mugonero. These include chlorination, slow and rapid sand filtration, ceramic candle filtration, Filtrons, boiling, and UV irradiation. A thorough trade study was conducted to identify appropriate water treatment approaches to address these water treatment goals. The results of the trade study are summarized below, including identified benefits and drawbacks for application in Muramba and Mugonero. The results of the trade study are summarized in Table 3.

The trade study concluded that family-sized disinfection systems were impractical because of the replacement and maintenance costs and labor were all outside the means of a typical Rwandan family. Therefore, the team decided to work with the Muramba Clinic and the Mugonero Orphanage, which would each be responsible for maintaining the systems. The Clinic would provide access to residents living nearby, while the Orphanage system would be used primarily by the children. For this type of community scale system, UV disinfection was determined to be the optimal solution for rapidly disinfecting a containers' worth of water brought to the Muramba Clinic or the Mugonero Orphanage. UV offers high treatment effectiveness and cost effi-

TABLE 2. Water Treatment System Requirements.

Parameter	Requirement	Considerations
Bacterial Contamination	Reduce contamination (specific level not defined, as water quality varies and any improvement is presumed to benefit community[7], but target is the elimination of all coliform bacteria).	May be affected by seasonal variations in source water quality.
Time	System must provide treated water in less than five minutes after influent water is added.	Most people already spend time fetching water and do not want to spend excessive time waiting for treatment.
Influent Water	System should work for both continuous and intermittent use, with varying influent water quality.	Water treatment will be required by families at different times of the day, and at varying volumes and quality throughout the day and year.
Cost	System must have a per-liter maintenance cost affordable to the served family or community.	Some Rwandan families have less than ten dollars cash per year for purchasing goods such as clothing or medicine.
Materials	Utilize locally available materials as much as reasonably feasible.	'Local' may be defined to include community-level and country-level, including imported goods depending on how reasonably the parts can be obtained; may use materials in implemented system of higher quality than those available in Rwanda as long as materials with comparable performance can be obtained locally.
Quantity	Treat approximately 5,000 liters per day (supplies about 500 persons)	Varies depending on population and season.
Maintainability	System maintenance must be easily performed by local trainees.	May involve training local maintenance personnel with some infrastructure experience.
Reproducibility	System design should be able to be reproduced by local communities trained in the design.	May be on a household or community scale, depending on complexity and nature of design.
Sustainability	System must operate successfully for at least five years without continued support from EWB-USA.	Initial implementations may involve follow-up by EWB-USA before design and education weaknesses are resolved.

ciency for the large volume of water needed, whereas the other treatment options were determined to be impractical for cost, cultural or volume considerations. While UV irradiation is capable of treating a bucket of water rapidly with minimum maintenance, UV has some distinct drawbacks. The main issues that had to be addressed in system design were the requirement for low-turbidity input water and the requirement for a source of replacement lamps.

System Design

The trade study concluded that no single off-the-shelf water treatment system was appropriate for Muramba or Mugonero. Instead, EWB-USA developed the Bring Your Own Water Treatment System (BYOW) that combines proved water treatment techniques in a unique assembly with innovative features appropriate for these communities. BYOW-I was installed at the Muramba Clinic in June 2006,

TABLE 3. Trade Study Results.

Technology	Advantages	Disadvantages
Boiling	Common in the developing world	Firewood is expensive, time consuming, and not readily available
Coffee Filters	Can use local materials	Cost; slow filtration rate
Rapid Sand Filter	Can treat varying volumes and quality of water, uses simple technology and local materials	Does not offer total decontamination; can be technically complex.
Slow Sand Filter	Can provide thorough decontamination using very basic, widely available materials	Large media bed areas, slow flow rates, and may require additional maintenance over an intermittent rapid sand filter
Solar Cooker	Utilizes sunlight for disinfection	High cost; Requires large area
SODIS (Solar Disinfection)	Recycles plastic bottles, easily understood and implemented	Bottles can be expensive; slow disinfection rate
Filtron	Uses locally available materials, can be a marketable skill	Replacement cost is outside the means of most Rwandan families; slow filtration rate
Electrical UV	High filtration rate; low maintenance costs	UV lamps not generally available in developing communities; requires added training to ensure safety; often requires pretreatment to lower input turbidity
Chemical	Chemicals available in most countries; very effective when used properly	Can be misused; taste is not appreciated by most communities
Source water protection	Simple masonry constructions	Difficult to protect surface water sources in Rwanda given dense population. Wells are not feasible in most locations given mountainous terrain.
Rainwater catchments	Reliable source of water	Tanks and gutters are expensive for most communities. Stored rainwater is generally not up to drinking standards without additional treatment.

and BYOW-II was installed at the Mugonero Orphanage in August 2007.

The input device of the "Bring Your Own Water Treatment System" (BYOW) consists of an open bucket placed on an elevated platform. Users pour into the bucket turbid and bacteria-contaminated water collected from nearby streams and taps. The water is passed through a plastic 55-gallon drum containing either an array of settling tubes tilted at 60 degrees or an up-flow gravel roughing filter (depending on configuration). A small portion of the input water is automatically diverted to an adjacent drum for eventual backwashing of the system, and the bulk of the water is piped to third drum approximately 15 feet lower. This lower drum, known as the "Plastic Drum Sand Filter" or "PDSF", is a rapid sand filter containing six inches of gravel supporting 15 inches of sand topped by six inches of pumice gravel. The water is forced by gravity through this rapid sand filter, and then passes through a UV sanitation sub-system powered by photovoltaic energy. The UV sub-system is operated by a timer controlling both the UV light and an electronic water valve.

A schematic for the complete BYOW system, in the roughing filter configuration used in Mugonero, is shown in Figure 3 with components identified by reference designator in Table 4. This figure shows the nominal flow path of the water under treatment,

FIGURE 3. A schematic of the BYOW system detailing the main components and the flow path of both the filtration water (passing through '5') and backwash water (through '7').

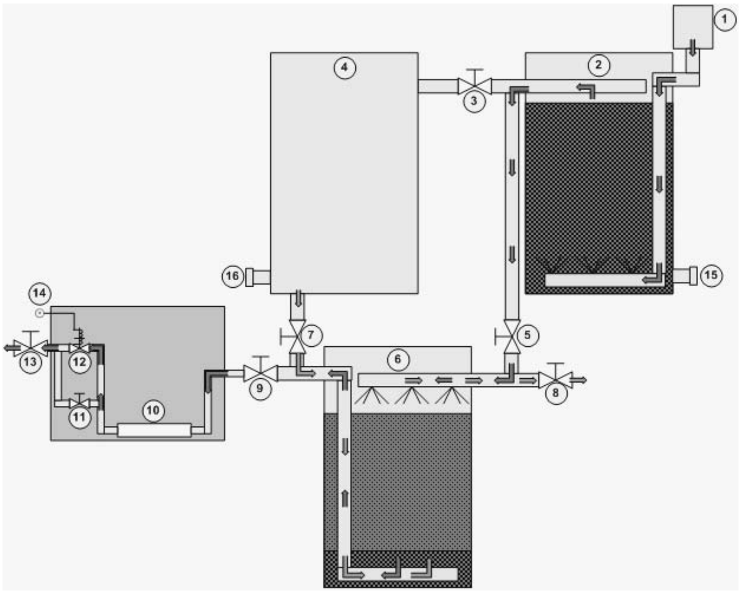


FIGURE 4. CAD rendering of complete assembly.

as well as the water used in backwashing operation. The input bucket, rouging filter and backwash tank are located on a hill above the PDSF and UV components. One of the innovative aspects of this system that is noteworthy is that the energy required to drive the system both nominally and in backwash operation is provided by the sun and the user. The cumulative result is a system that can treat a five gallon bucket (about 20 liters) of water in about two minutes using solar and human power alone. Figure 4 shows a CAD rendering of the complete assembly.

The BYOW Treatment System combines several water treatment approaches. The first treatment step in the system is either an inclined tube settler or a gravel roughing filter, depending on the configuration used. Incoming water enters the bottom of this filter drum and travels up through the tubes or gravel. As the water travels through the drum, gravity causes entrained sediment to sink downward. In the gravel filter configuration, sediment is contained below the input distribution arm, thereby minimizing further re-entrainment. This configuration has proven to have superior performance to that of the tube settler configuration.

TABLE 4. BYOW components.

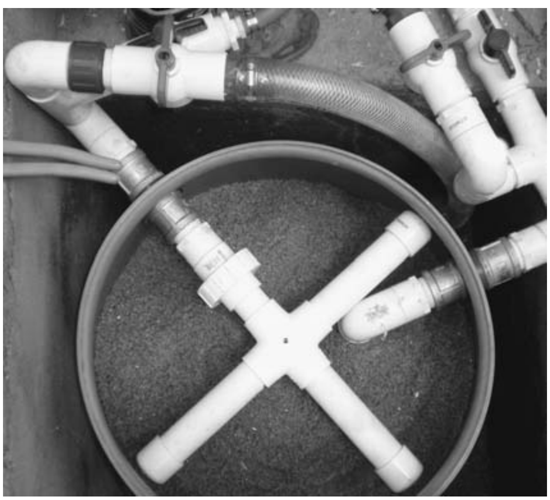
1. Input bucket
2. Roughing filter
3. Backwash diversion valve
4. Backwash tank
5. Rapid sand filter inlet valve
6. Rapid sand filter
7. Backwash inlet valve
8. Backwash outlet valve
9. UV box inlet valve
10. UV light
11. UV box manual bypass valve
12. UV box solenoid valve
13. UV box outlet valve
14. System "On" button
15. Roughing filter drain
16. Backwash drain

Next to this settling tank is a backwash tank that automatically diverts a portion of the input water and stores it for later backwashing of the rapid sand filter. The automatic diversion is accomplished by a valved branch in the plumbing that acts as a weir, shunting a fraction of each input slug to the backwash tank. The remainder of the slug travels onward to the PDSF which is located a few meters below.

The bulk of the water is piped downhill, with the vertical drop of 10-15 feet (3-5 meters), providing pressure for the Plastic Drum Sand Filter. This small rapid sand filter is built from a plastic watertight 55 gallon drum with a removable lid. The filter operates under hydrostatic pressure to maximize filtration speed. In the Muramba implementation, the PDSF operates at a maximum pressure of 14 feet of water (6 psi, 41 kPa). Under nominal operation, water flows to the sand filter through a 1/2-inch vinyl hose. The small hose diameter increases average pressure at which the filter operates and throttles volume so as to increase the time treatment water is exposed to the treatment processes. The cross-shaped distribution arm is mounted on a PVC union fitting that allows the arm to be removed to facilitate maintenance access to the media bed. The PDSF is shown in Figure 5.

The filter media resides in the central portion of the PDSF, between the distribution arm and the underdrain. The media is supported by a six-inch layer of gravel which prevents the media from entering the underdrain. The primary media used in this implementation is sand with an effective size (D_{10}) of about 0.6 mm. This is the typical size for sand in a rapid sand filter[8]. This sand forms a layer 15 inches deep. Above the sand is a six-inch layer of pumice gravel which pre-filters the water so as to lighten the filtration load on the sand and lengthen the interval between backwashes. Its larger size and lower density causes the pumice to remain floated on top of the sand.

FIGURE 5. Top view of the PDSF showing the media bed, distribution arm, and four external valves.



Water is forced through the media by pressure from the column of water above it, removing particulates and bacteria. Because system pressurization is provided by each bucket of water added, the amount of treated water delivered to the user can be no greater than the amount introduced. This prevents users from taking more water than they have provided to the system. Additionally, the treated water is delivered within minutes, because the sand filter is already primed and pressurized with water added by previous users. The PDSF in the BYOW system differs from typical sand filters and borrows principles from both rapid and slow sand filter designs. The biggest departure from usual design is the minimal pretreatment before filtration. While typical filters have pretreatment processes or other types of influent control, the PDSF influent is quite variable with the only pretreatment process being the sedimentation unit. The predictable result is that the filter will clog more rapidly and the effluent will be of lower quality then in a typical RSF based plant[8].

While traditional rapid sand filters require frequent service, the PDSF employed in the BYOW system is configured to significantly reduce operational maintenance. The rapid sand filter in this system is oversized relative to the anticipated loading rate of the system. This deviation from the traditional set of parameters reduces the maintenance interval of the filter by more than an order of magnitude. This reduction in maintenance requirements allows the rapid sand filter to be maintained by a single person who attends to the filter once every few weeks.

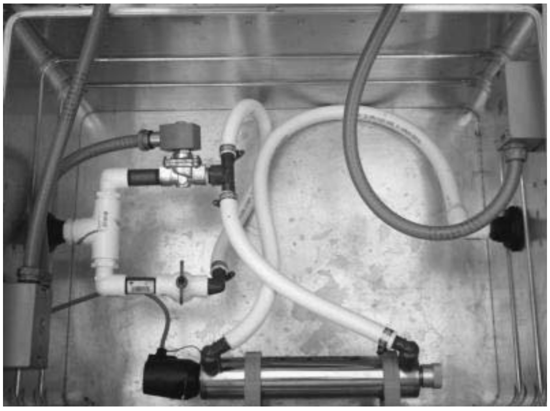
As water travels through the media bed during normal operation, contaminants are removed by physical, chemical and sometimes biological processes. These contaminants accumulate in the voids between the media granules and eventually clog the filter, preventing it from passing water at an acceptable rate. At this point, the media needs to be washed to remove the accumulation of contaminants and allow the filter to pass water again. This washing action is achieved by discharging a large amount of water upward through the media in a process known as backwashing. By passing a large volume of water through the media in the opposite direction of normal filtration, backwashing removes accumulated debris. To achieve this effect without a pump, the system must be installed with a large elevation differential by installing the input section 12-18 feet higher than the sand filter component. The hydrostatic head generated by this elevation differential is used to power the filter backwash process. An added benefit of this elevation difference is that filtration takes place under significant pressure, thus increasing the speed of treatment to approximately 10 liters per minute.

During nominal operation, filtered water flows out of the PDSF into a solar-powered UV reactor. The UV radiation deactivates much of the remaining bacteria in the water. One major drawback of UV is the fact that it requires high-tech components such as a power source and a supply of specialized lamps. The challenge of a power source was addressed by integrating the system with a photovoltaic power system. After implementing a solar-powered lighting system at the Muramba Clinic in January 2006, the EWB-USA team was confident that clinic personnel would be able to properly operate and maintain the nearly identical PV power system for the UV unit. The second challenge of finding replacement lamps for the UV disinfection unit was addressed by working with a water system supply store in Kigali that can import the lamps at a reasonable cost for Muramba. Because the communities regularly source medicine and materials from Kigali, this was a minor added burden. The Clinic and Orphanage were willing to assume this responsibility because the BYOW system directly addresses waterborne illness, the biggest public health challenge in the region. It is anticipated that successful use of the BYOW system will reduce illness-related costs at both the Clinic and the Orphanage.

The Ultraviolet disinfection system utilizes an off-the-shelf commercial disinfection unit and ballast, the R-Can Environmental Sterilight line (12 or 20 lpm units depending on configuration). The system is stored in a waterproof, locked Zarges aluminum box. The necessary electrical and plumbing connections are also enclosed in the box, shown in Figure 6. The system is operated by actuating a push-button switch on the outside of the box. This switch turns on the UV system ballast, proving power to the light for a timed interval, while also actuating an electrical solenoid valve (shown at top of picture in green) to allow the water flow through the system. In some configurations, the valve is on a delay timer to allow lamp warm-up. However, should the valve fail, it can be easily be bypassed and water flow provided by a standard hand valve. The UV lamp is enclosed in a protective quartz sleeve that is transparent to UV radiation while protecting the lamp from the water. Power is provided to the UV lamp ballast and solenoid valve via the external power interface visible in the upper left hand corner of Figure 6. Power is provided by a waterproof cord transmitting AC power from the solar panel power supply located in an adjacent building. The power cable is protected by a conduit and buried beneath a concrete walkway.

The UV lamp is designed to operate for 365 days of continuous use. Because the lamp will only be running for a few hours per day, it is anticipated that one lamp will last at least two years. Should the UV lamp fail or wear out, the UV ballast has a beep alarm designed to alert the user when the lamp needs to be replaced.

FIGURE 6. Inside of UV system box.



The manufacturer of the commercial UV unit does not recommend intermittent use of the system because it decreases lamp lifetime. But, because the BYOW system is used for much less than 24 hours per day, it is predicted that the trade-off in duration will favor the BYOW application. Additionally, the effect of a recommended warm-up time of the UV unit is being investigated for further BYOW iterations, and possible changes to BYOW operating procedures.

The UV system is powered by a 50 or 102 watt solar-panel power supply, depending on the configuration. The total draw of the disinfection system is approximately 40 watts. The PV installation is sized to provide power to the system for about seven hours per day, or at 5,000 least liters per day. The photovoltaic power supply system was designed to account for losses from temperature, wiring, and battery, charge controller and inverter efficiencies. The losses due to temperature were obtained from determining the average temperature and peak sun hours in Rwanda. The NASA surface solar energy website provided this information[9]. Storage is provided by a single 200 amp-hour 12-volt truck battery which was purchased in Kigali.

While the UV stage of the BYOW system is considerably higher technology than the PDSF and settling tank, temporary failure of the UV would not completely disable the BYOW system, as users would still receive filtered water better than the average input.

Nominal Operation

Water treatment with the BYOW system begins when a user pours water from a container into the input bucket at the upper level of the system. The act of adding water provides the hydraulic energy needed to drive the water through the treatment processes. The user then carries the now-empty container down to the output side of the system at the bottom of the wall. The user places the container under the output faucet and activates the electronic timer switch. Treatment takes about two minutes for a typical 20-liter jerry can of water. Untreated water droplets remaining in the user's bucket are diluted with many liters of treated water, though the Mugonero community has chosen to designated pre- and post-treatment containers for storing water because decaying fruit is often found in the bottom of collection cans.

Because treatment water is stored in the three treatment processes at any given time, users do not receive the same water that they poured into the input bucket. Rather, the user's added water serves to displace an equal volume of water through each of the treatment processes. By design, it is not possible to take more water out of the system than a user puts in. Water will only come out of the faucet if the system is being driven by an addition of water from the user.

In addition to backwashing, regular maintenance includes cleaning of the settling tank and the electronic output valve, UV lamp replacement, PV system maintenance, and hydraulic line and media replacements as needed.

Performance Analysis

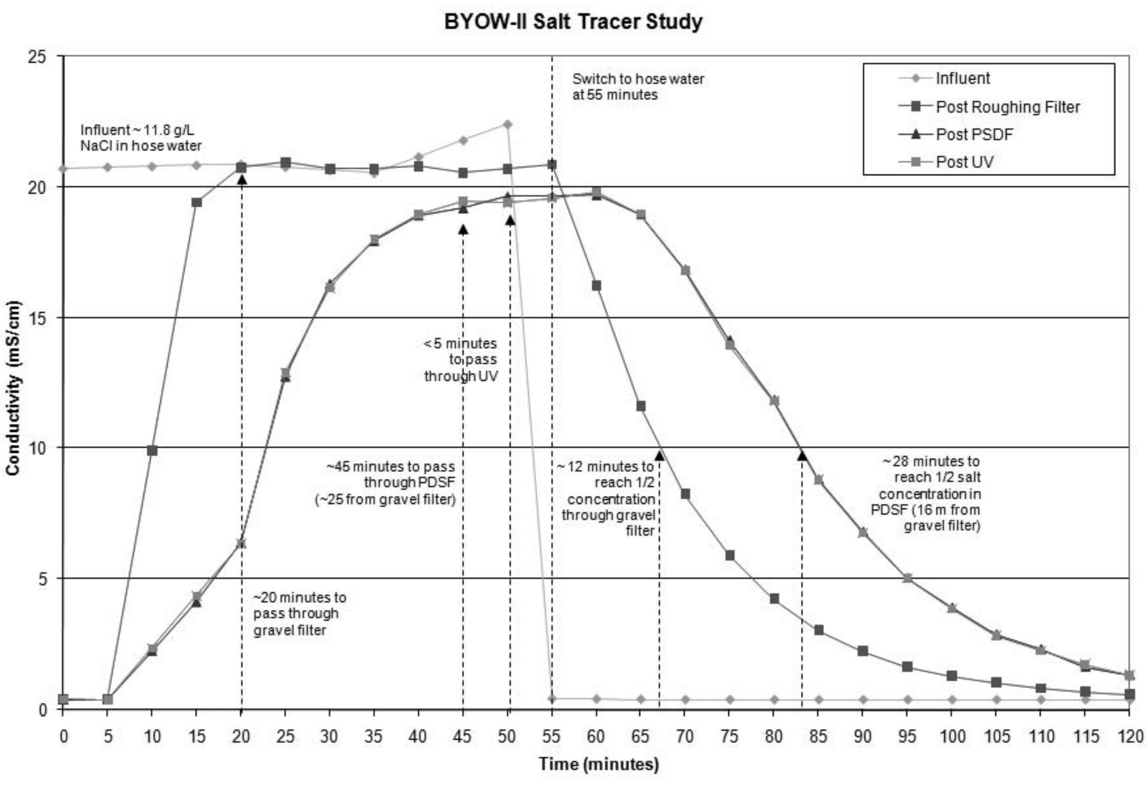
The BYOW system is designed to provide a high volume of water to residents currently drinking turbid and bacteria-contaminated water. The BYOW system may not always bring water quality up to first world standards, but rather will quickly increase the quality of water for residents accustomed to drinking water of poor quality. This is consistent with other similar efforts, "in most developing countries, the imperative is to get from "bad" quality (more than 1,000 fecal coliform per 100 milliliters) to "moderate" quality (less than 10 fecal coliforms per 100 milliliters), not necessarily to meet the stringent quality standards of industrial countries."[7] Additionally, the system will not replace all sources of water for a resident, as some exposure to local microorganisms can be advantageous to maintain a natural disease resistance.

A rapid sand filter has turbidity reduction characteristics of between 0.3 log to 0.5 log, and 0.3 log to 1 log reduction of E. Coli[10]. Based on a range of inputted turbidity and E. Coli counts, the resultant anticipated performance is calculated. These results indicate that for turbidity the PDSF anticipated performance is to reduction between 50% and 70%, and for E. Coli between 50% and 90%. The UV system effectiveness is impacted primarily by the quantity and nature of particulates. Some studies indicated a UV dose reduction of 2.5% per NTU.[11] The anticipated average BYOW performance was not less than a 70 percent reduction in bacteria counts, regardless of input turbidity, and close to 100 percent bacteria reduction at less than 50 NTU input turbidity at ~4 lpm, and 95 percent reduction at less than 30 NTU and ~30 lpm.

This anticipated performance was then complemented by a field study on each BYOW configuration before implementation in Rwanda. First, a salt tracer study was conducted to characterize the residence time of the processed water in each of the treatment stages. The tracer study involved inputting ~12 g NaCl / liter water solution into the system at 9 lpm for 55 minutes, then switching to clean water. Conductivity measurements of the influent, post-roughing filter, post PDSF and post UV water samples were taken every five minutes. The results of this study are presented in Figure 7. These results indicate that at a flow rate of 9 lpm the roughing filter residence time is approximately 20 minutes, while the PDSF residence time is approximately 25 minutes. These estimates are made on the amount of time needed for each subsequent stage to reach a steady conductivity, indicative of salt concentration. These results were important to consider when designing the long term test such that test points of effluent accurately reflect influent water treated.

The BYOW system was then challenged with activated sludge, a byproduct of wastewater treatment, as the primary contaminant in the influent water. Activated sludge was used because it is primarily bacteria flocs, and therefore the turbidity in the water tracks bacterial contamination well. This long term test involved an automated batch dosing system that mixed activated sludge with clean water and then pumped the mixture into the system at a rate of approximately seven liters per minute. Each batch was approximately 100 liters, and around seven batches were run per day separated by two hour intervals. In total, about 8,800 liters of wastewater at around 75 NTU (measured with a Hach 2100P Turbidimeter)

FIGURE 7. BYOW-II Tracer Study.



was pumped into the BYOW-II system over ten days. The test was stopped when the effluent flowrate had reduced to about one-third of a liter per minute because of media fouling. Turbidity results for this test are presented in Figure 8. E. Coli colony forming unit (CFU/ml) results (collected with 3M Petrifilm plates) are presented in Figure 9.

The turbidity results show that the roughing filter performs most of the filtration while the sand filter successfully finishes the filtration to bring the turbidity down to less than one NTU. This is explained by the batch nature of the process wherein particulates are introduced to the roughing filter and allowed to settle below the input distribution arm between batches. The UV light successfully deactivates most of the remaining bacteria. The bacteria results show that the system is consistently bringing the concentration of bacteria down from several thousand colonies to two or less.

A backwash of the system was then performed with water than had been diverted to the backwash tank during a previous test from the roughing filter, as is nominal operation, and left to sit for several weeks. The turbidity of this water was 2.24 NTU before backwashing. This water was then run through the PDSF. The effluent went from 64.7 to 28.4 NTU over the 2.5 minutes of the backwash. The system was then switched back to nominal operation, and run at seven liters per minute. The effluent water was immediately 0.98 NTU, falling to 0.72 NTU after 1.5 minutes, 0.68 after 3 minutes, and 0.36 after 5 minutes. These results indicate that minimal flushing volume is needed to maintain sand filter filtration performance at less than 1 NTU after backwashing.

These results indicate that the BYOW concept is extremely effective at decontaminating influent water, and supports confidence in the systems' performance in Rwanda.

FIGURE 8. BYOW-II Turbidity Reduction Performance.

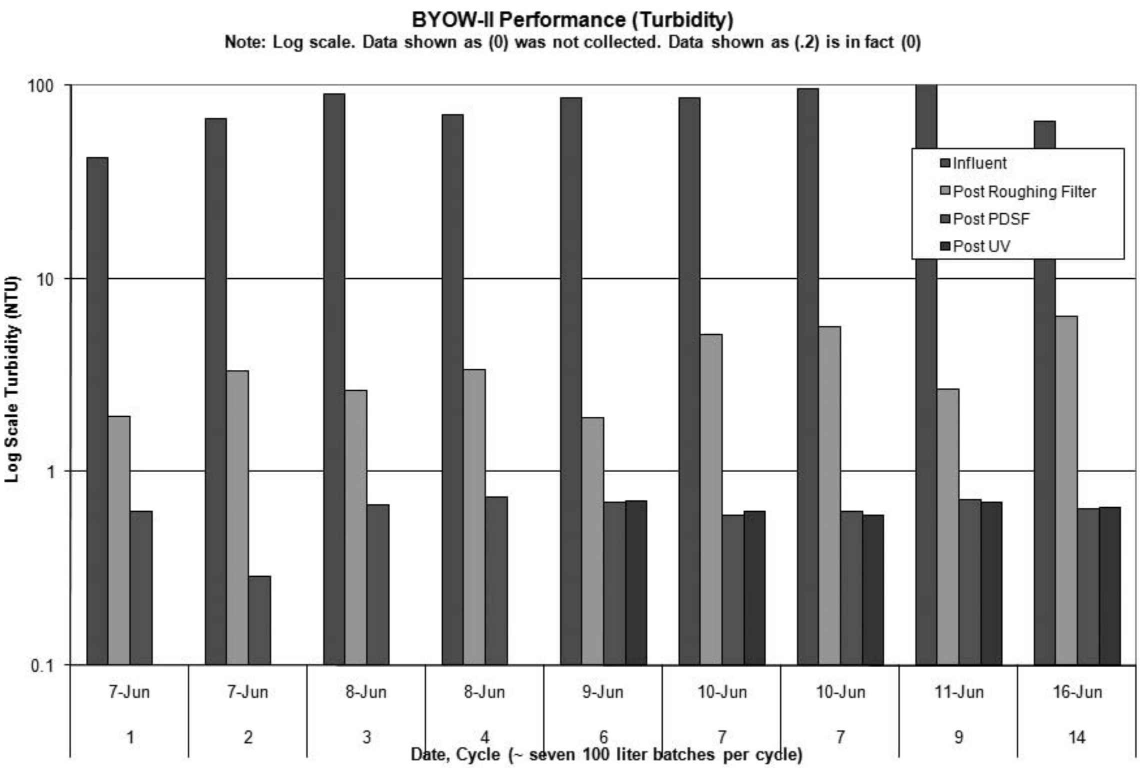
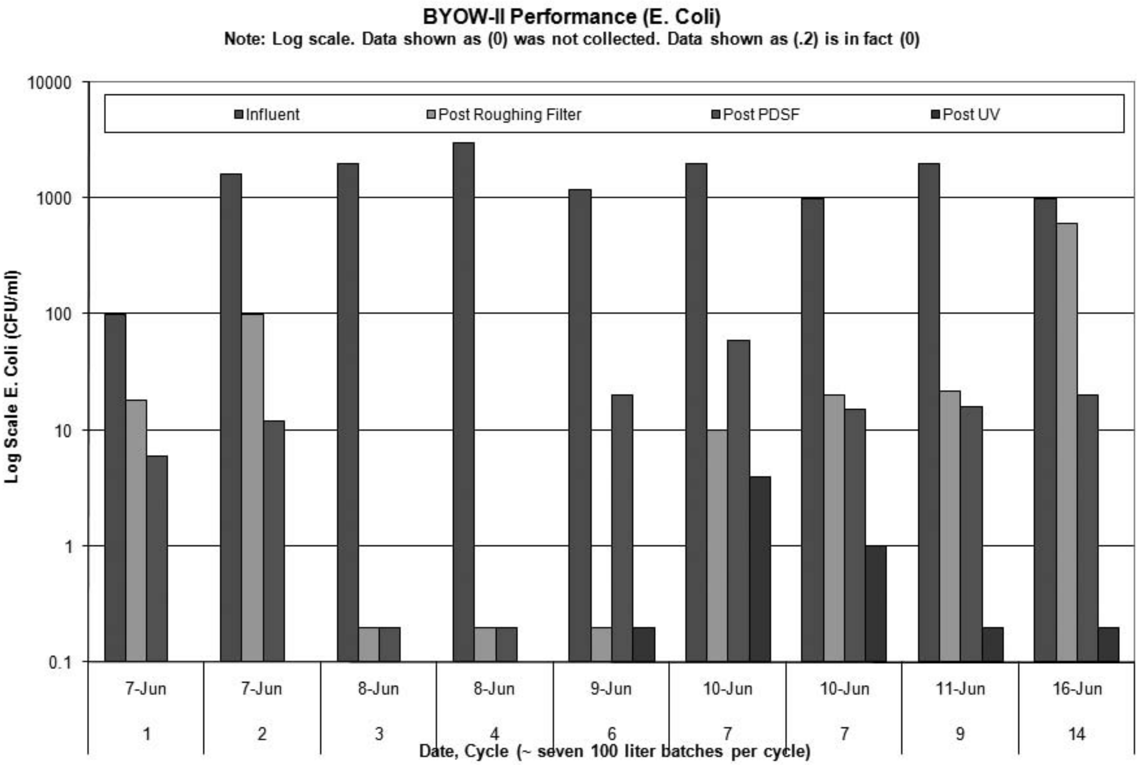


FIGURE 9. BYOW-II Bacteria Reduction Performance.



IMPLEMENTATION

The BYOW systems were fully prototyped, tested, and the field units constructed in the United States before each departure to Rwanda. However, all materials used to construct the system were also either available in Rwanda or importable through existing channels.

The original plan dictated that the systems would be installed on steep hills. However, upon arrival in Muramba in June 2006, a large retaining wall was used instead. The approximately 14-foot high retaining wall was located in an ideal location on the clinic grounds, well within the patrol range of the clinic security guards. In addition to being in a particularly safe and convenient location, the retaining wall also featured a built-in stair case that would serve as an ideal path for users between the input and output sections. A year later, the next system was installed at the Mugonero Orphanage atop a half-finished water cistern that was completed for the project, with welded metal stairs and railings added. The completed systems are shown installed at the Muramba Clinic in Figure 10 and Mugonero Orphanage in Figure 11 with EWB-USA and Rwandan volunteers.

The first step in installing the BYOW systems was to construct the masonry housings. This was done by a team of masons hired in the local community under the supervision of the EWB-USA construction foreman. The three component drums were then assembled, tested for leaks and installed within the housings. Concurrently, the PV power system was installed on a nearby building and connected to the UV disinfection unit.

The gravel was first sifted to remove dust and debris and then washed by hand in a small basin until the wash water was no longer visibly turbid. This clean gravel was loaded into the bottom of the filter

FIGURE 10. The completed BYOW Treatment Systems installed at the Muramba Clinic in June 2006.

FIGURE 11. The Mugonero Orphanage in August 2007.

body to a depth of six inches. Ungraded, sediment-laden sand collected from a dry river bed was sifted using 2 mm and 0.5 mm mesh. The sand that fell outside this range was discarded. The graded sand was washed by hand and loaded into the filter body above the gravel to a depth of 15 inches.

In Muramba, with the system completely assembled and the media cleaned and in place, the filter was backwashed repeatedly with a hose from a local tap until most of the residual silt in the media was removed. It took about 10 backwashes to reduce the turbidity of the output water from 40-44 NTU to 0-3 NTU. With the residual silt removed from the media, the system was ready for normal operation.

In Mugonero, to prime and flush the system, a 'bucket brigade' was mobilized by the orphanage residents to collect water from distant sources. After approximately 500 liters of water were poured through the system, the turbidity of the effluent was reduced to 9.5 NTU. After initial flushing, a 12 hour test was conducted on the system, inputting around 68 NTU water at one lpm, for a total throughput of 720 liters. After 12 hours, the effluent turbidity was 29 NTU out of the gravel filter and 8.5 NTU out of the PDSF. An additional round of flushing was then conducted with another 500 liters of water, further reducing the effluent to around 4 NTU. Because the influent flush water was around 5.2 NTU, further reduction of the turbidity will require extended use of the system. However, the UV stage should be effective at reducing the bacterial load in this effluent at around 5 NTU.

As with all EWB-USA projects, community maintenance of the system is critical to its long term success. To this end, local personnel were educated on the design, construction, operation, and maintenance of the systems. The EWB-USA team spent time throughout the construction process discussing the construction and design of the system and answering the questions of the people responsible for maintenance. Training included supervised practice in which trainees executed maintenance procedures without external assistance, until they were competent and comfortable in the tasks.

To facilitate continuing education, placards in French and English were mounted next to each system detailing its operation. In addition, an operation manual was provided to the system operators.

RESULTS

Water Quality

Following hydraulic testing, preliminary water quality tests were conducted in Muramba in 2006 for a variety of water quality parameters. The results indicated that the effluent water quality was high, with turbidity between 0 and 3 NTU, and total coliforms between 0 and 2 CFUs/ml. However, the influent water quality was comparably high because of the season and the availability of a local tap. During periods of lower water quality, the performance of the system is expected to be more pronounced. One such period is during the rainy seasons, when runoff washes more contaminants into collection points. Another situation where the input water would be significantly more contaminated is when the pipelines around the clinic are turned off, which occurs with some frequency. When these lines are off, water is collected from rivers which are often highly contaminated.

In July 2007, shortly before the implementation of the BYOW system in Mugonero, the EWB-USA team visited Muramba to further assess the first system. The treated water was of poorer quality than expected. Through investigation and interviews with community operators, it was determined that the system had fallen into disuse for a period of months because of internal community disagreements regarding maintenance responsibilities. This disuse resulted in the sand media fouling and contaminating the effluent water. It is proposed that the sand media served as a bioreactor, allowing biofouling of the sand media during the extended periods of disuse. Rather than contaminants being contained on the top of the media layer, biofouling had grown throughout the drum. This behavior is not expected with proper use and maintenance of the system, allowing a constant flow through the media. After cleaning the sand media and refurbishing the system, EWB-USA negotiated with the community to secure proper maintenance of the system in the future, ensuring a throughput of at least 100 liters per day.

Upon initial start-up of the BYOW-II system in Mugonero, the effluent turbidity was around 5 NTU. EWB-USA left a turbidity meter and Petrifilm bacteria plates in Mugonero, and after more than two months of use by the community, a local

TABLE 5. Mugonero Orphanage water quality results.

Date	Rainwater Turbidity (NTU)	Rainwater bacteria plates (CFU/ml)		BYOW Turbidity (NTU)	BYOW bacteria plates (CFU/ml)	
		Total Coliforms	E. Coli		Total Coliforms	E. Coli
9/10/07	4.65	1	0	2.07	0	0
9/13/07	4.03	2	0	2.25	0	0
9/16/07	4.52	2	0	1.85	0	0
9/18/07	3.81	1	0	2.01	0	0
9/20/07	3.56	0	0	2.04	0	0
9/24/07	2.31	20	1	2.02	0	0
9/26/07	2.21	25	0	1.9	0	0
9/30/07	4.42	32	0	1.92	0	0
10/2/07	3.75	45	0	1.90	0	0
10/4/07	3.45	63	0	1.93	0	0
10/7/07	3.11	33	0	1.95	0	0

volunteer reported water quality results for both the rainwater catchment systems and the BYOW system. The results, shown in Table 5, show that the integrated rainwater catchment / BYOW approach is successfully delivering clean water to the community.

As shown, the turbidity out of the rainwater catchment tanks ranges from around 2–5 NTU, with bacteria loads as high as more than 60 CFUs/ml, while the BYOW system reduces the turbidity to around 2 NTU and eliminates all viable bacteria. It is anticipated that further use of these systems will increase the bacteria count in the rainwater catchment tanks during dry season storage, while further use of the BYOW system will reduce the effluent turbidity.

Community Response

EWB-Rwanda volunteer Jean Pierre Habanabakize visited Muramba to interview the community on use of the system. Muramba Clinic nurse Nzabonimpa Jean Damascene reported that the BYOW system was being used by staff, patients, mothers of newborn babies, teachers, students and other residents. Culturally, the system continues to be adopted by an increasing number of residents. The initial greatest challenge reported was "mentality of some elders in the community who said that the taste of water is different than they were used to. The nurses and staff have explained the importance of drinking treated water, and detailed the operation of the BYOW system. Now the elders have started to change their mind slowly, and the number of people who use the system increases every day."

These residents believe that, "the BYOW water treatment system is useful for their water purification, and they see it as very important in their life. They think that if they use it they and their children will no longer fall sick of diarrhea. Residents also say that since the system is free of charge it would be a loss not to use it. . . . the people who use the system appreciate it and they are very happy. This is proved by their reaction, when ones come and treats water, he or she returns home and encourages neighbors to use the system for water treatment; by these actions the idea is spreading everywhere and the number of people using the system is increasing."

The Muramba Clinic counts the BYOW system, "among the remedies it can use in curing diarrhea and some other diseases which are caused by the unclean and contaminated water that the people in Muramba drink. This is our community's answer to such diseases, we will continue coordinating the campaign to increase usage of this system."

In September 2007, Victor Monroy, the director of the Mugonero Orphanage, reported to EWB-USA on the usage of their recently installed BYOW system. Mr. Monroy reported, "The Children's Village did not have water available on site for the past six years. Every single drop of water was fetched from a relatively long distance. The children invested an enormous amount of time and energy with the daily water supply activities. The only available alternative to drink pure water was to boil it. That caused to the orphanage very high expenses to purchase big amounts of firewood. Due to the long and relatively complicated process of boiling water, quite often the children decided not to boil the water. The fact of drinking unclean water caused many health problems to our children. Quite often the children suffered from digestive and intestinal problems. Due the work and efforts of EWB-USA the situation has changed dramatically. Now there is plenty of pure water available to cover all the needs of the orphanage. The water purification system has the capacity to filter over 5,000 liters of water daily. To boil such an amount of water we would need to burn mountains of firewood every single day. That is not necessary at all due the very efficient and effective UV filter, powered by a small solar system. Now all the children have more than enough pure water to have a healthy and happy life. Thanks to the knowledge and experience of EWB–JSC all our children can drink all the water that they may want having the security that it is almost 100 percent pure. We are convinced that the health of all our kids will improve considerably through the precious and abundant supply of pure drinking water."

The Muramba and Mugonero communities are working closely with EWB-USA to monitor the performance and usage characteristics of the BYOW systems. Parameters of interest include input and output water quality, source of water input, number of people using system per day and per season, maintenance tasks, and backwash interval. These monitoring steps are conducted over email, and planned visits by EWB-USA.

DISCUSSION

The BYOW system was designed to minimize any hazards implementation could present to the communities. The most likely worst case would be that the system does not provide enough benefit to justify the community's effort in maintaining and operating it. Secondarily, improper maintenance of the system can result in decreased water quality. However, both of these concerns are currently being addressed through experience and training. Other hazards, including mercury in the UV lamp and long-term stagnation of the water in the system, are being addressed by proper training and increasing usage.

In Mugonero, the installation of the BYOW-II system occurred in parallel to the installation of six 10,000 liter rainwater catchment systems. These rainwater catchments are projected to provide a reliable source of rainwater throughout the year. However, rainwater by itself, though generally cleaner than surface water, was not found to be sufficiently clean for potable needs, especially during extended storage during the dry seasons. Bacterial flocs will likely form in the tanks that must be treated. In combination with the BYOW-II system, the Orphanage should now have a reliable and on-site source of clean drinking water.

The BYOW system is designed to increase access to cleaner water than residents are currently consuming, and thereby reduce exposure to disease causing microorganisms. The BYOW system is not designed to treat all water consumed by residents, as some exposure to these microorganisms may help maintain an acquired disease resistance. Along these lines, the untreated droplets remaining in a user's bucket are diluted by the treated water, and likely are not an additional hazard. Finally, bacterial regrowth concerns after UV irradiation are mitigated by the expected consumption of water within a day of treatment.

The total cost of installing the BYOW system was about $2700. The only major recurring cost in the maintenance of the BYOW system is periodic replacement of the UV lamp. Replacement cost of the lamp is estimated to be about $100, including all import taxes and shipping fees. A worst-case estimate of bulb replacement every six months translates to a cost of 0.027 cents per liter. Assuming a ten-year system lifetime and current usage numbers, this works out to less than 0.06 cents per liter of water treated. The typical unskilled laborer in rural Rwanda may make about a dollar per day. Assuming he or she consumes three-to-four liters of water per day, the cost of clean drinking water is less than one-third of one percent of personal income.

Because the BYOW systems are evolving prototypes, both EWB-USA and the communities recognize that continued involvement by EWB-USA over the next several years will help ensure success. With continued development, the team believes that the BYOW system could become an attractive option for communities looking for a low-cost, community-scale water treatment solution that can be constructed with locally available skills and materials.

In the short term, the system's success will be measured by use of the systems for treating residents' water and reduced prevalence of water-borne illnesses at the Muramba Clinic and Mugonero Orphanage. Long-term success will be measured according to continuing community maintenance of the system and its replication elsewhere in the region.

CONCLUSIONS AND FUTURE WORK

By the nature of volunteer work, implementations of the BYOW systems have been confined to once per year. While this is immediately benefiting these communities, larger scale implementations are achievable without sacrificing quality, sustainability, or appropriateness. Recent ventures in partnership with the Manna Energy Foundation in Houston, the United Nations Development Program in New York and Kigali, and the Rwandan Government may provide for the earning of Certified Carbon Emission Reductions (carbon credits) for BYOW water treatment. These Kyoto carbon credits would be generated by the suppressing of demand for non-renewable wood to boil the water. Such carbon credits could potentially fund hundreds of implementations per year, and pay for close monitoring and maintenance by trained staff.

Cost optimization of the BYOW design will continue to enable system replication for the poorest communities. This includes investigating the use masonry tanks instead of plastic drums, and the use of a slow sand filter instead of the relatively expensive UV disinfection subsystem.

This effort includes development of a Plastic Drum Slow Sand Filter (PDSSF) which, if successful, would allow for the replacement of the UV disinfection component in favor of a lower-tech slow sand filter approach for the final treatment step. The PDSSF (which may also be implemented in masonry housing) will have an increased bed size over the PDSF by having several filter bodies in parallel operation, and is targeted to have comparable decontamination performance as the UV system.

The EWB-USA team is also developing a modularization of the BYOW system so that components may be installed individually or in concert in a variety of scenarios including flatland situations and pipeline interfaces, and with various media beds, including polyethylene foam, textiles, diatomaceous earth, coconut fiber, burnt rice husks, ceramics, anthracite coal, and activated carbon.

The BYOW concept is a promising appropriate technology solution for densely populated developing communities. Additional research and development efforts are aimed to realize the potential of the BYOW system as open source technology for addressing public health challenges in the developing world.

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