Field Evaluation of Long-Term Performance and Use of Biosand Filters in Posoltega, Nicaragua

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An evaluation was conducted in 2007 on biosand filters that were installed in Posoltega, Nicaragua in 1999 and 2004. The objectives were to characterize the condition and use of filters eight and three years after installation, determine filter performance of those filters still in use, and identify determinants of successful long-term use and performance. Methods consisted of household identification, user questionnaires, and water quality testing. Of the 234 filters installed, only 24 were found to still be in use. Average log reductions were 1.73 (98%) for total coliforms, 1.36 (96%) for Escherichia Coli, and 0.91 (88%) for turbidity. Statistically significant effects were detected for the magnitude of the contamination of source water, the peak hydraulic loading rate, and the standing depth of water over the filter media. Questionnaire results indicated user training on filter maintenance could improve the peak hydraulic loading rate and hence filter performance. The low rate of sustained use (10%) is an indication of failed implementation, and is attributable to structural failure, particularly cracking of the concrete filters from 2004. Nonetheless, this evaluation demonstrated the biosand filter technology to be robust since those filters still in use were performing as expected three and eight years postimplementation.

Key words: biosand filter, household water treatment, point of use, developing countries, Nicaragua

Introduction

Access to clean water, free of pathogens and other contaminants, is essential for human life and vital for the development of healthy communities. Nonetheless, there are 1.1 billion people worldwide without access to safe drinking water, and there are 1.6 million deaths every year attributable to the lack of access to safe drinking water and basic sanitation; 90% of these deaths are among children under the age of five (WHO 2005). The majority of these cases are in rural areas of developing countries, where centralized distribution systems do not exist or are unable to provide clean water to the community. A novel approach that has been forwarded by the World Health Organization (WHO) and other water, sanitation, and health policy makers worldwide is Household Water Treatment, where a family takes responsibility for treating their own drinking water through the application of a household-based technology. Dr. Jamie Bartram, Coordinator for the Water, Sanitation, and Health Programme of the WHO, states that “there is now conclusive evidence that simple, acceptable, low cost interventions at the household and community levels are capable of dramatically reducing the risks of diarrheal disease and death. These household interventions are cost-effective, with an overall benefit of up to 60 US$ per 1 US$ invested” (Sobsey 2002, forward).

One type of household water treatment technology is the biosand filter, which is an intermittently-operated, small-scale slow-sand filter. The biosand filter consists of a housing structure (typically concrete or plastic) that contains a column of approximately 0.5 m of fine sand. The sand is underlain by a granular underdrain and an outlet pipe which rises up the wall of the structure to discharge at a point higher than the sand column, thus maintaining a standing depth of water in the filter, and the media in an aqueous environment. The biosand filter is used by charging the top of the filter with a bucket of water, and collecting the filtered water from the outlet pipe. A diffuser plate above the standing water depth disperses the flow and reduces impact on the biological layer (discussed below), which is important for water treatment. The low construction and installation costs, ease of use, minimal maintenance requirements, and simple self-contained design make it an appropriate technology for application in remote and rural locations of developing countries. The earliest biosand filters were introduced in the Nandaime Valley of Nicaragua as a pilot project in 1993 (Manz et al. 1993). The technology has since spread to more than 140,000 households across 38 countries (S. Kaczmer, Centre for Affordable Water and Sanitation Technology, personal communication, February 1, 2008).

A traditional slow-sand filter relies on a naturally occurring biological layer, or schmutzdecke, within the top depth of sand to treat contaminated water. Influent waterborne pathogens that pass through this layer are removed through “inactivation (degradation and/or predation), physical straining, and attachment to the sand grains” (Dullemont et al. 2006). A traditional slow-sand
filter can remove between 1 and 3 log units of coliform bacteria (Amy et al. 2006), between 2 and 4 log units of enteric viruses (Amy et al. 2006), and up to 4 log units of Giardia cysts and Cryptosporidium oocysts (Amy et al. 2006). As an intermittently operated slow-sand filter, the biosand filter also relies on the biological layer at the top of the sand for the removal of influent waterborne pathogens. Laboratory evaluations of the biosand filter have demonstrated its ability to consistently remove up to 2 log units of faecal coliforms (Buzunis 1995) and Escherichia coli (Stauber et al. 2006), and up to 4 log units of Giardia cysts and Cryptosporidium oocysts (Palmateer et al. 1999). Another laboratory evaluation found geometric mean reductions of 1.9 log units for E. coli and 2.1 log units for echovirus 12 (Elliott et al. 2008). These evaluations indicate that in the laboratory setting, the efficiency of pathogen removal by the biosand filter is consistent with that of a traditional slow-sand filter.

Pathogen removal by the biosand filter has also been evaluated in a number of field studies (Table 1). The majority of these studies were field reports from implementing organizations that undertook limited water quality testing on recently installed filters to demonstrate the short-term success of this technology; these field reports did not typically undergo any peer review process. It is only within recent years that peer-reviewed papers have been published on the long-term efficacy of biosand filters installed in homes and communities (Stauber et al. 2009; Duke et al. 2006).

A randomized controlled trial was recently conducted in Bonao, Dominican Republic to document the reduction in diarrheal disease following biosand filter intervention. The results indicate households that received filters exhibited a 47% reduction in diarrheal disease compared with control households, “indicating a significant effect of the [biosand filter] against waterborne diarrheal disease” (Stauber et al. 2009). Before the intervention, water quality sampling indicated geometric mean concentrations of E. coli in the source water of 22 and 21 MPN/100 mL (MPN = most probable number) for intervention and control households respectively; following the intervention, households that received biosand filters exhibited an average reduction of 48% in drinking water concentrations of E. coli over the course of the six-month study period (Stauber et al. 2009).

To provide further evidence on the long-term efficacy of the biosand filter as an intervention for improving drinking water quality, an evaluation was conducted in 2007 on biosand filters that were installed in 1999 and 2004 in Posoltega, Nicaragua. The objectives of the study were to:

- Characterize the physical condition and operation of the biosand filters eight years and three years after implementation (i.e., post-1999 and -2004, respectively);
- Determine the performance (measured as coliform and turbidity removal efficiency) of the biosand filters still in operation;
- Identify the determinants of long-term performance and use of the biosand filters in Posoltega, Nicaragua.

Baughen et al. (1999) undertook a field study at the same location during the initial introduction of the filters to Posoltega in 1999; the availability of this data provided an additional point of reference in evaluating the filter performance.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Organization</th>
<th>Country</th>
<th>Time since installation</th>
<th>Indicator organism</th>
<th>Removal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manz et al. (1993)</td>
<td>University of Calgary</td>
<td>Nicaragua</td>
<td>3 to 8 weeks</td>
<td>Fecal coliform</td>
<td>99%</td>
</tr>
<tr>
<td>Buzunis (1995)</td>
<td>University of Calgary</td>
<td>Nicaragua</td>
<td>3 weeks</td>
<td>Fecal coliform</td>
<td>97%</td>
</tr>
<tr>
<td>Baughen et al. (1999)</td>
<td>University of Calgary</td>
<td>Nicaragua</td>
<td>1 month</td>
<td>Fecal coliform</td>
<td>80%</td>
</tr>
<tr>
<td>Mol (2001)</td>
<td>Medair</td>
<td>Kenya</td>
<td>3 weeks</td>
<td>Fecal coliform</td>
<td>93%</td>
</tr>
<tr>
<td>Dies et al. (2003)</td>
<td>Clean Water for Nepal</td>
<td>Nepal</td>
<td>&quot;Recently&quot;</td>
<td>E. coli</td>
<td>95%</td>
</tr>
<tr>
<td>Bojcsik &amp; Jergil (2003)</td>
<td>Uppsala University</td>
<td>Mozambique</td>
<td>1 month</td>
<td>Cyanobacteria</td>
<td>96%</td>
</tr>
<tr>
<td>Fewster et al. (2004)</td>
<td>Bushproof – Medair</td>
<td>Kenya</td>
<td>2.5 to 4 years</td>
<td>Fecal coliform</td>
<td>70% &lt;10 cfu/100mL</td>
</tr>
<tr>
<td>Stauber et al. (2006)</td>
<td>University of North Carolina – Chapel Hill</td>
<td>Dominican Republic</td>
<td>1 year</td>
<td>E. coli</td>
<td>94%</td>
</tr>
<tr>
<td>Duke et al. (2006)</td>
<td>University of Victoria; CAWST</td>
<td>Haiti</td>
<td>5 years</td>
<td>E. coli</td>
<td>98.5%</td>
</tr>
<tr>
<td>Earwaker (2006)</td>
<td>Cranfield University – Silsoe</td>
<td>Ethiopia</td>
<td>5 to 7 years</td>
<td>E. coli</td>
<td>88%</td>
</tr>
</tbody>
</table>

*CAWST = Centre for Affordable Water and Sanitation Technology.
Setting

The rural communities of the Municipality of Posoltega have limited infrastructure. Communal drinking water systems are not available, and families rely on individual shallow wells for their source water. Previous studies have shown these wells are contaminated with pathogens and pesticides (CIRA 1999a, 1999b).

In October of 1998, this region was ravaged by Hurricane Mitch. Widespread flooding and a landslide resulted in two buried villages and approximately 2,300 deaths. In 1999, a nongovernmental organization (NGO) taking part in the relief effort following Hurricane Mitch manufactured biosand filters at their facility in Managua, Nicaragua and delivered them to 34 families in the community of El Trianón (Baughen et al. 1999). Approximately half of these filters were plastic structures, and half were concrete. In 2004, the same NGO returned to Posoltega to aid in the construction and deployment of 200 more concrete filters. These filters were built by community members at the local health center in Posoltega for the purpose of replacing defective filters in El Trianón and delivering new filters to households in the communities of San Gilberto, Posolteguilla, Buenos Aires, El Mojón, and San Agustín. A map of Posoltega identifying the communities that received biosand filters is shown in Fig. 1. Schematics of the concrete filters and plastic filters installed in these communities are included in Fig. 2.

**Fig. 1.** Map of Posoltega and study communities. Sources: U.S. Department of State (2007) & INETER (2006).
Materials and Methods

The field investigation, conducted from January to April 2007, began with a systematic identification of the households where biosand filters had been installed, and where these filters were still in use. All filters that were found to be in use were inspected for their physical characteristics, and water quality testing was conducted on the source water and filtered water to determine filter performance. Household members were interviewed regarding the use and operation of the biosand filter, as well as other water and sanitation practices.

Household Identification

Researchers from the University of British Columbia and support staff from the local health centre visited the six communities (Posoltega, San Gilberto, Posolteguilla, Buenos Aires, El Mojón, and San Agustín) where filters were installed to identify those that were still in use. In El Trianón, every household in the community was visited to identify working filters and determine the failure mechanism in defective filters. In the communities of San Gilberto, Posolteguilla, Buenos Aires, and El Mojón, the high failure rate of the filters meant that houses with working filters were common knowledge and easily identified through communication with community members. In addition, approximately half of all households in these four communities that had received filters were visited to determine the failure mechanisms of those filters not in use. In San Agustín, a meeting with the community leader revealed that not a single filter was still in use on account of failure of the structure. Throughout the entire Municipality of Posoltega, biosand filters were being used in 24 households.

All 24 households with working filters were included in the filter evaluation component of the study. Nine of these households were selected for two more follow-up visits (a total of three visits each) to conduct additional water quality testing. The purpose of further testing was to provide a level of confidence in the results and estimate the variability in the results over the time period between visits. These nine households were selected to provide balanced representation of the different filter types (plastic or concrete), implementation years (1999 or 2004), communities, and water quality results encountered during the initial visits.

Household members consented to participate in two steps. During the initial visit, household members verbally consented to a visit by a study team member at a later date for data collection. During the second visit, household members gave their consent again, as evidenced by their actions in responding to the questionnaire. The University of British Columbia Behavioural Research Ethics Board approved the study.

Biosand Filter Inspection

The inspection process for biosand filters consisted of recording the location, implementation year, and structural material (concrete or plastic), checking the integrity of the structure for cracks and leaks, and ensuring the diffuser plate and lid were in place. The standing depth of water over the sand during the pause period between filter charges when there is no influent water was indicated by Buzunis (1995) to be an important operational parameter of the biosand filter. Diffusion of oxygen through this standing water depth is thought to keep aerobic organisms in the biological layer alive. The flow rate (hydraulic loading rate) has been found to be an important operational parameter for both traditional slow-sand filters (Hendricks and Bellamy 1991) and biosand filters (Buzunis 1995; Duke et al. 2006).

Standing water depth was measured before charging the filter with water. The flow rate through the filter was measured by recording the time to fill a 250-mL cup with water from the filter outlet after charging the top reservoir of the filter with a 20-L bucket of source water. The biosand filter operates under a falling head regime, and therefore this measurement was taken immediately after charging the filter so as to record the peak flow rate (which decreases with the falling head) and to ensure consistent measurement technique between filters. The volumetric flow rate was then normalized by the cross-sectional area, approximately 0.058 m² (24 by 24 cm) for the concrete filters and 0.086 m² (33-cm diameter) for the plastic filters, to yield the peak hydraulic loading rate in m³/m²/hour.

Questionnaire and Observational Data

A questionnaire was administered by the research team at each household, typically to the female head of household. The interview was conducted in Spanish and consisted of 43 questions covering family demographic information, water use, operation of the biosand filter,
and sanitation practices within the home. Filter users were also asked about training and any follow-up received from the implementing organization. Additional observational data was also recorded on the construction materials and layout of houses, condition of wells and latrines, and general level of hygiene.

Interview questions that related to filter operation included estimation of the total filtered volume per day (daily loading rate), filter sharing practices between families, frequency of filter maintenance, length of time since the last filter maintenance, and use of any other treatment methods.

**Water Quality Testing**

The evaluation of filter performance was based on removal of microbial indicator organisms and turbidity. The indicator organisms selected for this study were total coliforms and *E. coli*. While abundant in the intestine of warm-blooded mammals, *E. coli* is not typically able to thrive outside of the host. This organism is therefore used as an indicator of recent fecal contamination, and potentially fecal-derived pathogenic organisms (Feng et al. 2002). The WHO explicitly states that *E. coli* “should not be present in drinking-water” (WHO 2006); testing for *E. coli* allows for comparison to this standard.

Samples of the water were taken before it was introduced into the top of the filter (source water), and immediately after it had left the spout of the filter (filtered water). To evaluate the entire delivery system in its ability to provide clean drinking water, a third sample was taken from the stored filtered water currently being used as the family’s source of drinking water (discussed in Vanderzwaag [2008]).

Standard Method 9222: Membrane Filter Technique for Members of the Coliform Group (APHA et al. 2005) was used for the enumeration of coliform bacteria in the sample water. Membrane filtration was conducted in the field using Potatset WE10005 (Wagtech International, Berkshire, U.K.). Field sterilization of the equipment was achieved through the combustion of methanol as per the manufacturer’s operation manual [Wagtech International [no date]]. The growth media m-coliBlue24 (Hach Company, Loveland, Colo.) was selected for this study for the simultaneous detection and differentiation of total coliforms and *E. coli*. The differential media contains enzymes which cause coliforms to produce red colonies by their ability to reduce TTC (2,3,5-triphenyltetrazolium chloride), and *E. coli* to produce blue colonies by their ability to hydrolyze the enzyme substrate BCIG (5-bromo-4-chloro-3-indolyl-beta-D-glucuronide) to an insoluble salt, while suppressing the growth of noncoliform organisms (Hach Company 1999).

Preliminary testing of the source water revealed such high levels of microbial contamination that the number of organisms in a 100-mL sample would have been too concentrated to produce evaluable results. Furthermore, the preliminary testing suggested significant variation in organism concentrations, thus testing sample volumes differing by an order of magnitude would improve the likelihood of achieving evaluable results for both indicator organisms versus testing a single sample volume. In light of this, sample volumes of 1 and 10 mL were taken of the source water, and sample volumes of 10 and 100 mL were taken of the filtered water. The 1-mL samples were measured using sterile, single-use pipettes; the 10-mL samples were measured using sterilized glass beakers; and the 100-mL samples were measured by filling the reservoir tube on the membrane filtration equipment to the appropriate indicated mark.

The prepared specimens were transported to the local health center in Posoltega where they were incubated at 35°C for 24 hours. After the incubation period the colonies were enumerated with the assistance of a 5× magnification handheld lens and a tally counter. Concentrations below detection limits were recorded as 0.5. The results were factored according to the sample volume, and reported as CFU per 100 mL. Where both the small and large sample volumes yielded enumerable results, the plate count within or closest to the range of 15 to 150 CFU was selected, and a coefficient of variation between the two results was computed. This approach is discussed further and evaluated in Vanderzwaag et al. (2009). A digital photograph was also taken of each series for record keeping. Two blank samples per day were taken for quality control, representing 11% of all samples.

The turbidity meter Wag-WT3020 (Wagtech International, Berkshire, U.K.) was used to measure turbidity, in nephelometric turbidity units (NTU), of the water samples in the field. At least five readings were recorded for every sample, and the geometric mean of these readings was reported and used for subsequent analysis. This instrument was calibrated every day using the supplied control vials.

**Statistical Methods**

The filtration efficiency was calculated as the log-reduction (LR) between the paired source and filtered water quality results from the household visit. For the nine households that were visited three times, the arithmetic mean LR was computed from the three visits and used as a single data point in subsequent reporting and analysis. Student’s *t*-test (two-tailed heteroscedastic) was used to test the statistical significance of the differences in means of two data sets, and the statistical significance of correlations. The Shapiro-Wilk test was used to test if a particular data set was consistent with a normal or log-normal distribution. Arithmetic means and standard deviations (SD) were reported for data sets consistent with a normal distribution, whereas geometric means and geometric standard deviations (GSD) were reported for data sets consistent with log-normal distributions.
Results and Discussion

Of the 234 biosand filters installed in Posoltega, Nicaragua during the 1999 and 2004 implementation programs, 24 filters were found to still be in operation in 2007. This is a rate of sustained use of 10%.

Water Quality Results

The water quality results for microbial and turbidity contamination varied over several orders of magnitude within each series for source and filtered water, and the distribution of each series was found to be consistent with a log-normal distribution by the Shapiro-Wilk test ($W = 0.94$ to $0.97$, $\alpha = 0.05$), hence geometric means and the respective geometric standard deviations (GSDs) are reported. Geometric mean source water concentrations were 13,000 CFU/100 mL (GSD = 3.9) for total coliforms, 130 CFU/100 mL (GSD = 8.9) for E. coli, and 1.5 NTU (GSD = 2.8) for turbidity. Geometric mean filtered water concentrations were 250 CFU/100 mL (GSD = 4.9) for total coliforms, 6 CFU/100 mL (GSD = 5.6) for E. coli, and 0.19 NTU (GSD = 2.6) for turbidity. These results are displayed in Fig. 3.

The field methodology of testing duplicate water samples at different volumes yielded 179 pairs of tests (358 results) where both the larger and smaller sample volumes yielded countable, useable results: 104 pairs for E. coli and 75 pairs for total coliforms. The average coefficient of variation computed between the results from the corresponding pairs of larger and smaller volumes was 51% (SD = 35%). Further discussion can be found in Vanderzwaag et al. (2009).

Filter Performance

The distribution of LR values was found to be consistent with a normal distribution by the Shapiro-Wilk test ($W = 0.955$ to 0.97, $\alpha = 0.05$), and therefore arithmetic means and the respective standard deviations (SD) of LR are reported. The mean LR was found to be 1.73 (SD = 1.05) for total coliforms, 1.36 (SD = 0.82) for E. coli, and 0.91 (SD = 0.63) for turbidity. The equivalent percent removal was 98% for total coliforms and 96% for E. coli. The equivalent percent removal was 88% for turbidity. Given that the source water turbidity was generally quite good with 48% reporting below 1.0 NTU and 67% reporting below 3.0 NTU, the expectation is that the biosand filter would be at least as effective in terms of turbidity removal for more turbid source water.

Out of a total of 72 LR values, five were negative, representing cases where filtered water exhibited higher concentrations than the source water. With one exception, negative LR values were bounded by approximately -0.3, representing a factor of 2.0 between the source and filtered water. The coefficient of variation between any two numbers that differ by a factor of 2.0 is 47%, which is within range of the coefficient of variation calculated above for the water quality testing methods. Those filters with poor filtration performance may therefore yield negative LR values as a result of the confidence intervals around the observed data points. These observations may also have resulted from biological processes within the filter itself, such as detachment, sloughing, or breakthrough, as discussed in Dullemont et al. (2006). The negative LR values did, however, correlate well with the linear models of determinants of filter performance discussed below.

The mean LR values of 1.73 (i.e., 98% removal) for total coliforms and 1.36 (i.e., 96% removal) for E. coli are within the expected performance range of a traditional slow-sand filter. These values are also within the expected performance range when compared with laboratory studies of the biosand filter (Palmateer et al. 1999; Stauber 2006), and with other field studies of the biosand filter (presented in Table 1). The results of this study found the filters to perform with greater efficiency than originally reported by Baughen et al. (1999) in the evaluation of the filters installed in 1999 (80%). This is likely due to the fact that the original evaluation was undertaken while the biological layer was still ripening in the recently-installed filters.

Evidence from this evaluation and the other studies in Table 1 suggests that the biosand filter technology is robust. Provided that the structural elements remain sound, biosand filters will continue to perform within the expected range of new (ripened) filters, even up to eight years after implementation.

Stauber et al. (2009) reported a reduction in the geometric mean drinking water concentration of E. coli by 48% from 21 to 11 MPN/100 mL, and a corresponding reduction by 47% in the incidence of diarrheal disease among households that used the biosand filter compared with control households. The improvements in water quality achieved by the biosand filters in the study in Posoltega were significantly greater, with geometric mean drinking water concentrations of E. coli reduced by 96% from 130 to 6 CFU/100 mL.

Nevertheless, the filtered water in this study does not for the most part meet the WHO guidelines for drinking water quality, which states that E. coli or thermotolerant
coliform bacteria must not be detectable in any 100-mL sample (i.e., 0 CFU/100 mL) of water directly intended for drinking (WHO 2006). Of the 24 filters tested, three (13%) yielded filtered water quality results of <1 CFU/100 mL E. coli, and 16 (67%) yielded results of <10 CFU/100 mL E. coli. This indicates that the biosand filters alone were not sufficient to provide clean water in this situation in the absence of additional treatment such as disinfection.

Determinants of Filter Performance

The performance of the biosand filters (measured as LR of total coliforms, E. coli, and turbidity across the filter) was found to correlate with the operational variables of source water contamination, hydraulic loading rate, and standing water depth, as discussed below. Given the many physical, biological, and chemical factors that affect filter performance for slow-sand filters (see Hendricks and Bellamy 1991; Pyper and Logsdon 1991; Dullemont et al. 2006) and biosand filters (see Duke et al. 2006; Stauber et al. 2006), the contribution of any one particular determinant may be low, resulting in the low coefficients of determination reported below. However, the findings at the significance level of α = 0.01 with n = 24 suggest the variables and measures of outcome are linearly related.

As shown in Fig. 4, the LR of E. coli across the biosand filter is related to the log of source water contamination (0.56, $R^2 = 0.42, p < 0.01$), as is the log of filtered water contamination (0.44, $R^2 = 0.31, p < 0.01$). This result indicates that the biosand filter follows the model, described by Hendricks and Bellamy (1991), of the linear relationship between the magnitudes of influent and effluent concentrations of heterotrophic bacteria in a traditional slow-sand filter. More importantly, it also clearly demonstrates that while filter performance is increased at greater source contamination, the filtered water contamination is nonetheless increased. Therefore, consideration of the source water quality is important when evaluating whether to use the biosand filter technology for achieving clean water.

The relationship between hydraulic loading rate and filtration efficiency in a traditional slow-sand filter is described in detail by Hendricks and Bellamy (1991) and Pyper and Logsdon (1991). These sources indicate that filtration efficiency improves at lower hydraulic loading rates. This relationship between flow rate and filter performance was detected for the biosand filters evaluated in this field study, as shown in Fig. 5. The peak hydraulic loading rate was found to have a negative effect on the LR of total coliforms ($-1.46, R^2 = 0.45, p < 0.01$), E. coli ($-0.93, R^2 = 0.31, p < 0.01$), and turbidity ($-0.68, R^2 = 0.28, p < 0.01$). This correlation was most significant for total coliforms, where the mean LR was 2.2 (SD = 0.93) for those filters with peak hydraulic loading rates below 0.6 m$^3$/m$^2$/h, and only 1.3 (SD = 1.0) for those with greater peak hydraulic loading rates; this difference is significant at the α = 0.05 level. Even though the biosand filter operates under a falling head condition, the results indicate that the hydraulic loading rate is still an important determinant of filter performance, akin to the slow-sand filter. A simplified model for explaining this phenomenon involves the relationship between pore-size in the biological layer; the screening, adsorption, and biological processes for pathogen inactivation within the layer; and the permeability of the layer as described by Darcy’s Law.

Laboratory studies have demonstrated that the flow rate through a biosand filter decreases over time as the biological layer develops (Buzunis 1995; Stauber et al. 2006). The time period since the last washing of the biological layer is therefore considered a determinant of the flow rate. Household members can ensure that their filters operate at the recommended flow rate by carefully regulating the frequency of filter maintenance. Unfortunately, much confusion was observed among the filter users in Posoltega regarding filter maintenance, suggesting insufficient user training. The users were divided almost equally into three groups: those that wash their filter when the flow is slow; those that wash their filter when the top appears dirty; and those that wash their filter on a regular schedule. The reported maintenance frequency, which varies from every second day to once every six months, averaged at 39 days (SD = 36). This suggests that filter users would benefit from training that included a more clearly defined maintenance frequency. While the optimum maintenance frequency for a particular filter is dependent upon many factors, including source contamination and daily use, the data suggest that allowing upwards of six months between maintenance cycles will not be detrimental to filter performance.

As shown in Fig. 6., the standing depth of water (in cm) over the top of the sand during the pause period when there is no flow was found to have a positive effect on the LR of total coliforms (0.10, $R^2 = 0.35, p < 0.01$) and E. coli (0.10, $R^2 = 0.49, p < 0.01$). Buzunis (1995) recommended that the standing depth of water be minimized so as to maximize the diffusion of oxygen through the water depth to the biological layer during the
The contrary results of this study suggest that other mechanisms may play a more significant role in filter performance than the oxygen transfer across the standing depth of water. Further investigation with a larger sample size of operational filters in the field is recommended.

No statistically significant relationship was detected between the total daily filtered volume and the filter performance (LR of total coliforms, \( E. \) coli, and turbidity, \( p > 0.05 \), data not shown). Biosand filters shared between different households were used to filter greater quantities of water, up to six buckets (120 L) per day. Yet, these filters were found to perform at the same level as those used to filter one bucket per day. This result suggests that sharing available filters in communities where access is limited may be a feasible option. Such a practice would encourage safe water behaviour among those individuals that are not currently filter users, thus contributing positively to community development.

No differences in performance were detected between filters constructed from different materials (plastic or concrete), installed in different years, or placed in different communities (LR of total coliforms, \( E. \) coli, turbidity, \( p > 0.05 \), data not shown). The finding that filter performance was unaffected by its structural composition is not surprising. The structural component is merely a container for the filter media, and only needs to be structurally sound in order for the filter to function. The finding that filters implemented in different years (i.e., 1999 or 2004) performed equally well suggests that long-term filter performance can be expected to remain constant, provided that the filter is used consistently and the structure remains sound.

In future studies, testing a random sample from a larger population of filters constructed from different materials, exposed to different usage habits and operational parameters, and placed in different communities would enable multiple comparisons and interactions of tested variables, and may yield additional information.

\[ \text{Fig. 5. Log reduction versus peak hydraulic loading rate.} \]

\[ \text{Fig. 6. Log reduction versus standing water depth.} \]
as a result of cracks developing in the structural body of the concrete filters, and outlet pipes becoming dislodged from the plastic filters.

Many of the 1999 filters reportedly broke when families tried to move them to a new community location following Hurricane Mitch. While the relocation was still underway, some families received filters at their homes in the original community location. When these families moved to their new homes, many of the filters were damaged during the transition. Other filters were abandoned altogether at the old homes when the families moved to their new homes or away from El Trianón completely.

The implementation of new biosand filters in 2004 and their subsequent failure was another indirect cause of failure of some of the filters from 1999. In these cases, the families in El Trianón that received a second filter in 2004 disassembled or abandoned their otherwise operational 1999 filter; when the 2004 filter failed, the family was left without any operational filter to use.

**Failure mechanisms of 2004 filters.** The most common reason for failure in the biosand filters from 2004 was significant cracking in the concrete walls, which resulted in water and sand leaking out of the filters. Even minor cracks caused water to drain below the top layer of sand, thus preventing the proper development of the biological layer. Leaks would also cause water to run on the ground or floor, creating an inconvenience to the user. With few exceptions, the leak in the structure prompted users to stop using the filter altogether, and to resume drinking water directly from the well.

The actual cause of the high incidence of cracking of the 2004 filters is not known with certainty at this time. Anecdotal evidence suggests that the concrete was not given sufficient curing time to achieve any significant strength and durability. Every individual interviewed regarding the filter construction activities indicated that filters were removed from their molds after one day of curing and almost immediately loaded onto carts to be transported across rural dirt roads to the communities. Many people from the community of San Gilberto made reference to “el golpe” (“the impact”) which further suggests a callous unloading procedure upon arrival at the destination household.

The difference in long-term durability between the 1999 and 2004 filters is likely a reflection of the fact that the 2004 filters were built by community members under the direction of the NGO technicians at the health center where quality control would be more difficult to maintain than in a dedicated facility in Managua. This indicates the importance of strict quality control during filter construction to ensure long-term successful use of the biosand filter.

**Conclusions**

This paper presents an evaluation of the biosand filters that were installed in Posoltega, Nicaragua in 1999 and 2004. The study was an evaluation of the in situ technology to characterize the condition of existing filters, determine the filter performance of operational filters, and identify the determinants of long-term use and performance of the technology. The major findings of the study are as follows:

- Of 234 filters installed, 24 were found to be in use. The rate of sustained use was 10%.
- Mean LRs of 1.73 for total coliforms, 1.36 for *E. coli*, and 0.91 for turbidity were determined. The equivalent percent removal was 98% for total coliforms, 96% for *E. Coli,* and 88% for turbidity. This is consistent with slow-sand technology, and other laboratory and field studies of the biosand filter.
- Source water quality is an important determinant of filtered water quality and filter performance. The biosand filter cannot deliver clean water as defined by WHO standards in isolation of consideration of source water quality and/or additional treatment involving disinfection.
- The peak hydraulic loading rate and the standing depth of water were also identified as important determinants of filter performance.
- No differences in filter performance were detected in filters from 1999 compared with filters from 2004. This suggests no long-term decrease in filter performance.
- For the other 90% of filters not in use, the greatest cause of failure was cracking of the concrete structure, likely a result of poor quality control during implementation.

The major findings from this evaluation indicate that implementation of household water treatment technology can fail if basic quality control is not practiced. However, in spite of the inadequate training of the users, this evaluation demonstrated the biosand filter technology to be robust. The 24 biosand filters were performing as expected in removing nearly 2 log units of coliform bacteria, eight and three years after implementation.

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