Recent advances in household biosand filter design

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The biosand filter is an intermittent-flow adaptation of slow sand filtration technology. Developed over 20 years ago and now with 15+ years' operating experience in households, it has established a reputation for effectiveness, durability, and sustained use. Research, field evaluations, and understanding of the nature of intermittent filter operation have led to advances in the design of the biosand filter as well as the specifications for the hydraulic loading rate, filtration sand, and pause period and requirements for maintenance and cleaning. Different methods of fabricating the filter body and diffuser basin are providing more alternatives for implementing biosand filter projects. As of December 2013, 500 organizations have reported implementing biosand filter projects in 59 countries, for a total of over 650,000 filters, impacting more than four million people (CAWST 2014).

Introduction

In 1991 Dr. David Manz developed a slow sand filter to be operated intermittently, thus making it more suitable for household applications. By making the highest point of the outflow tubing 5 cm above the sand, standing water covers the sand at all times allowing a biological community of bacteria and other micro-organisms to grow in the top 2 cm of sand. The biosand filter (BSF) stands about 1 m tall and is 0.3 m wide on each side, which makes it a convenient size for use in households. It is filled with layers of specially selected and prepared sand and gravel. The filter container is normally made of concrete or plastic.

The technology is especially relevant to families who do not have piped water and must carry their water into the home from a diverse variety of potentially contaminated sources (up to 50 NTU turbidity). Institutions such as schools, health clinics, community centers, prisons, and places of worship, can also utilize the BSF when piped water is unavailable or frequently contaminated.

Contaminated water is poured into the top of the BSF at least once per day (but not continuously). The water poured into the top of the filter passes through the holes in the diffuser, and flows down through the sand and gravel. Treated water flows out of the outlet tube. No power is required - the filter works by gravity. It takes about one hour to filter 12 litres of water. Most pathogens and suspended solids are removed through biological and physical processes that take place in the sand. These processes include: mechanical trapping, predation, adsorption, and natural death.

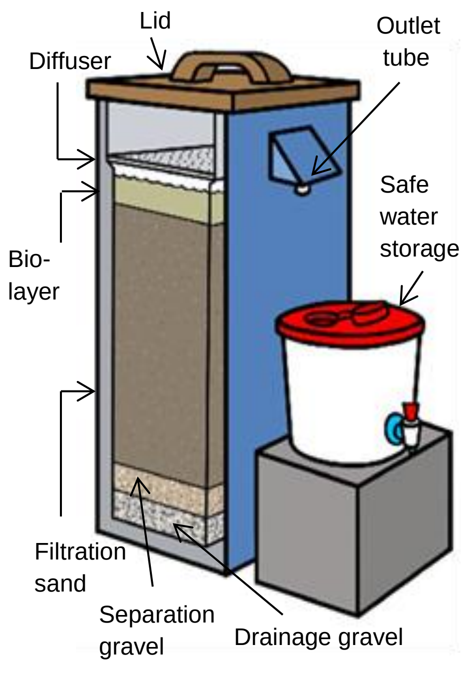

Figure 1. Biosand filter and safe storage container

Many of the recent advances in the design of the BSF pertain to the parameters that make the filter both effective in removing pathogens from the water and acceptable to the household in terms of ease of use and daily quantities of filtered water. These advances were derived from: a) research that has found ways to improve the BSF design, b) learning more about how the filter is used in the household, c) understanding the challenges of implementing BSF projects in developing countries, and d) determining the important parameters of the intermittent slow sand filter. Recommendations on how the BSF should be designed, constructed and operated are based on this new evidence.

Dimension changes

Table 1 provides a summary of the biosand filter (BSF) removal effectiveness measured in laboratory and field studies before the design changes discussed here.

Table 1. Treatment Efficiency of the Biosand Filter
Modified from CAWST (2011) *Biosand Filter Factsheet (detailed)*

	Bacteria	Viruses	Protozoa	Helminths	Turbidity	Iron
Laboratory	99%[1]	70 to >99%[1]	>99.9%[2]	Up to 100%[3]	75% to <1 NTU[1]	Not available
Field Studies	88% (75% of filters < 10 cfu/100mL), 99% (97% of filters < 10 cfu/100mL)[4,5]	Not available	Not available	Up to 100%[3]	85%[5]	90-95%[6]

[1] Elliott et al. (2008), [2] Palmateer et al. (1997), [3] Not researched. However, helminths are too large to pass between the sand, up to 100% removal efficiency is assumed, [4] Earwaker (2006), [5] Duke & Baker (2005), [6] Ngai et al. (2004)

The design of the biosand filter has evolved since 1991. Versions 1 to 8 were development designs that Dr. Manz advanced in the 1990s. Version 9 was a thinner-wall design to make the filter lighter to transport and less expensive to construct. Version 10 is described here.

The dimensions of the BSF include a reservoir volume (the maximum batch or fill that can be poured into the filter at one time) and a pore volume (the volume of the pore spaces within the filtration sand). The Version 9 BSF had a pore volume of 8.5 L and a reservoir volume of 18.5 L. This meant that when each batch of water was poured into the filter, the first 8.5 L of filtered water (effluent) was the water that had been retained in the pore spaces of the sand during the pause period, and the remaining 10 L of water flowed through the filter without any retention time. Bacterial removal was found to be substantially higher for the fraction of filter effluent which had remained in the pore spaces of the filter as compared to the water which had just flowed through (Elliot 2008). Research also determined that the filters performed better with lower pore velocities at the beginning of each run (Baumgartner *et al*. 2007, Tiwara *et al*. 2008).

In response to this research, in 2009 CAWST recommended that the standard concrete BSF design be modified. The height of the filtration sand layer in the filter was increased by 22%, from 45 cm to 55cm, while keeping the overall dimensions of the BSF the same. This design change meant that the pore volume of the filtration sand is increased to 12 L, while the reservoir volume is decreased to 12 L, so that virtually 100% of the filtered water is retained in the pore spaces of the sand during the pause period of the filter cycle. Also, by reducing the reservoir volume, the maximum head (i.e. difference between the highest water level and the level of the outlet) was reduced to 17 cm from 27 cm, decreasing the initial head pressure by 37%, which in turn reduces the maximum pore velocity. The increase in sand bed depth to 55 cm from 45 cm also resulted in increasing the ‘clean bed head loss’ (the head loss when the filter is first installed in the household), in the sand by 22%, reducing the maximum pore velocity further. The combination of reducing head pressure and increasing head loss thus reduced the overall filtration rate to no more than 400 L/hour per square metre of sand surface compared to 600L/hour per square metre in version 9. This greater volume of sand also provides more sand grain surface area for adsorption and attachment of contaminants, especially viruses. Finally, the diffuser and outlet spout were moved 10 cm higher to accommodate the increased sand, allowing more space for a safe water storage container below the spout.

This new concrete BSF design was termed CAWST version 10 (v10). Initial laboratory studies on the new version have shown average MS2 virus removal rates improving from 70% in the v9 (Elliot *et al.* 2008) to 99.99% or higher in the v10 (Wang *et al.* 2014).

Filtration rate and sand specifications

Kubare & Haarhoff (2010) state: "The filtration rate, or hydraulic loading, is the key design parameter for all filtration processes… the heart of BSF design thus lies in the careful and appropriate selection of the media and sizing of the media bed."

While the conventional slow sand filter (SSF) is a constant-rate process, the biosand filter (BSF) is a declining-rate process. For a given water temperature, it is the head loss in the filtration sand bed, combined with the available (declining) head, which determines the filtration rate. The flow control in the BSF is provided by the available head (determined by the design), and the head loss (determined by the sand sizing). Since the filtration rate varies during each run (with declining head) and between runs (with clogging of the sand bed over time), the target filtration rate is defined as the maximum rate that the BSF will encounter. This maximum filtration rate occurs when a filter is first installed in the household (the 'clean bed filtration rate'), and is measured at the start of the run when the filter is filled to the top.

Research, field evaluations, and consideration of the needs of the users in the household have led CAWST to set the recommended target maximum filtration rate at 400 L/hour per square metre of sand surface. Higher filtration rates cause high pore velocities that can scour the sand and cause pathogens to become unattached and re-enter the water stream. Lower filtration rates make the run time unacceptably long to the user, potentially causing them to drink unfiltered water instead. For the CAWST v10 filter, with a surface area of 0.06 m^2, this filtration rate provides a flow rate of 0.4 litres/minute. This measurement, made after the filter has just been installed, is a critical quality control parameter for the BSF.

The resistance to flow, or head loss, which is necessary to achieve the target filtration rate, is provided by the properties of the filtration sand and by the sand bed depth. The raw sand is processed into filtration sand to attain this target. Sieving the sand with a wire mesh or perforated plate sieve (opening size of 0.7 mm) to remove the oversize sand, then washing the sand with water as many times as necessary to remove sufficient amounts of the finer sand, will achieve the recommended ranges for the effective size and uniformity coefficient of the filtration sand.

A summary of the typical design parameters for the filtration sand and hydraulic loading rate for the BSF and the SSF is shown in Table 2. CAWST's recommendations for sand sizes are generally in a tighter range than what others studying the BSF have proposed, and also tighter than what are often used in the SSF. These more restrictive parameters are recommended to make it easier to achieve the target filtration rate.

Table 2. Typical design parameters for the BSF and SSF

Parameter	Biosand Filter (BSF)		Slow Sand Filter (SSF)**
	CAWST Recommendation	Recommendations by others*	
Filtration Rate/Hydraulic Loading Rate m^3/m^2/hour (or m/hour)	0.4	0.16 – 1.1	0.1 – 0.3
Effective Size, mm (d_{10})	0.15 – 0.2	0.15 – 0.3	0.1 – 0.3
Uniformity Coefficient (d_{60}/d_{10})	1.5 – 2.5	1.5 - 5	< 3
Maximum Grain Size, mm (d_{max})	0.7	-	-
Silt content, %, (d < 0.1mm)	< 4%	-	-
Filtration Sand Bed Depth, m	> 0.5	> 0.4	0.6 – 1.0

* Lukacs (2002), Hillman (2007), Manz *et al*. (1993), Fewster *et al*. (2004), Baumgartner *et al*. (2007), Duke *et al*. (2006) ** Fox *et al*. (1994) and Campos *et al*. (2002).

Note: Sediment size d_{10} is defined as the grain diameter at which 10% of the sediment sample is finer than. Sediment size d_{60} is associated with 60% finer than.
Source: Adapted from Kubare and Haarhoff 2010

Pause period

A major difference between the slow sand filter (SSF) and the biosand filter (BSF) is the pause period. The intermittent flow of the BSF means that, unlike the SSF, there is a period of time in the filter cycle when the water is retained in the pore spaces and the filtration rate/velocity of the water through the pore spaces (pore velocity) is effectively zero. The total retention time (RT) includes the pause period time plus the run time when the water is being filtered through the sand.

Kubare and Haarhoff (2010) state that the pause period is of importance from three competing perspectives:

1. The treatment efficiency is improved because the water stored in the pores of the filtration sand undergoes further quality improvement during this time. Filter effectiveness is generally improved with longer pause periods.
2. The biological layer (biolayer or Schmutzdecke) requires an inflow of nutrients to establish and remain viable. More frequent batches of water (shorter pause periods), will be better from this perspective.

Quantity of filtered water produced by the BSF needs to be sufficient for the household's daily needs. With shorter pause periods, more filtered water will be available for the family.

Jenkins *et al*. (2011) and Elliot *et al*. (2008) found that operating the filter with a long pause period between batches improved performance for bacteria, virus, and turbidity removal when compared with no pause period. This was especially true of virus removal.

CAWST (2011) recommends a pause period of 6 to 12 hours with a minimum of 1 hour and maximum of 48 hours. The maximum pause period is to ensure that in hot arid climates the 5 cm of standing water (supernatant) does not dry out and kill the organisms in the biolayer. Household water requirements for treated water, typically about 40 L/day, mean that the v10 filter (with a 12 L batch capacity) will generally be filled 3 or 4 times per day. This would be equivalent to 6 to 8 hour pause periods if the batches are evenly spaced in time, however in practice it is likely that the pause period would be longer at night, and would also depend on household water collection habits.

Cleaning and maintenance

The cleaning and maintenance process is significantly different between the biosand filter (BSF) and the slow sand filter (SSF). Both types of filters will clog over time with particles and other materials that accumulate in the top 1 – 2 cm of the filtration sand.

An advantage of the BSF is that it is small enough to 'clean in place', using a technique that restores the flow rate without the need to remove the sand. In the BSF, when the flow rate becomes too slow, the user is advised to perform maintenance by 'cleaning'. Fewster *et al.* (2004) suggest this occurs when it takes more than about two hours to filter a batch of water. With the small sand surface area in the BSF, the top 1 – 2 cm of sand can be cleaned manually by filling the reservoir with about 4 L of water, removing the diffuser, swirling the top of the sand with the palm of the hand to stir up the dirt, then scooping out the dirty water with a small container and dumping it into a soak pit (or the bushes). The steps in this 'swirl-and-dump' technique are repeated as many times as necessary to restore the flow rate. Normally it requires 15-20 minutes for cleaning the BSF in this manner.

Because it disturbs the biolayer, filter performance declines immediately following a maintenance event. No systematic peer-reviewed research has yet been conducted on the process of filter recovery following maintenance, so CAWST recommends that BSF users be more diligent about disinfecting filter effluent for the week following filter maintenance. Jenkins *et al.* (2011) found that disturbance of the biolayer by cleaning had no measurable effect on virus removal and only a modest reductive effect on bacterial and turbidity removal seven days after the disturbance.

Diffuser basin

The diffuser slows down the water from rushing into the sand layer and disturbing the biological layer essential to pathogen removal (CAWST 2012). This is important because the velocity of the poured water would otherwise cause disturbance of the biolayer allowing the influent water to bypass that layer and flow through the top portion of the sand without benefiting from the removal mechanisms (or the head loss) that the biolayer provides.

A study by DACAAR (2012) in Afghanistan found diffuser basins having 81 to 144 holes of 1 mm and 2 mm in diameter do not cause any disturbance to the top of the fine sand layer and the biolayer. Jones (2013), of the British Columbia Institute of Technology in Canada, reported similar results – diffusers with too few holes (25), too many holes (225), or too large holes (4 mm) will significantly disturb the fine sand layer and the biolayer, and subsequently resulting in lower removal of total coliforms (Cusworth, 2014). CAWST recommends BSF implementing-organizations use diffuser basins with 64 to 144 holes of 1.5 to 3 mm diameter.

The original versions of the concrete BSF used diffuser plates rather than basins. They were made with a narrow ledge cast into the concrete on all four interior walls of the BSF concrete body. This ledge, located 2 cm above the level of the water during the pause period, provided the location for the diffuser plate (typically a flat sheet made from plastic or metal) to rest on. Results of 25 BSF field evaluations in 16 countries found 26% of diffuser plates were damaged and/or incorrectly placed in the BSF (Ngai *et al*. 2012).

Diffuser basins use the same size and number of holes as the plates, but differ from plates in that diffuser basins have side walls which extend up to a lip around the top of the basin, so they rest on the top of the filter walls. Diffuser basins prevent any water from escaping around the sides which was a frequent problem with the plates. Basins are more convenient than plates to remove and replace in the filter. Basins also make the fabrication of the concrete BSF easier and less expensive since the ledge is not required. Recently, a diffuser basin for the concrete BSF, made from injection-molded plastic, has been developed which is durable and appears robust enough to last as long as the concrete BSF (15+ years).

Iron-amended BSF

Iron-amended biosand filters (BSF) have been created by the addition of zero-valent iron such as common iron nails, iron chips or iron particles either into the diffuser basin or mixed directly into the BSF sand bed. These have been found to enhance virus, bacteria, and arsenic removal (in comparison with the sand-only BSF). The corrosion of the iron creates continuous formation of new iron oxides (rust). The mechanism for the removal/inactivation of pathogens and arsenic is through electrostatic attraction with positively-charged iron oxide providing adsorption sites for negatively-charged arsenic and virus particles.

In a two-year evaluation of over 1000 Kanchan Arsenic Filters (KAF, BSFs amended with iron nails in the diffuser basin) deployed in rural villages of Nepal, Ngai *et al*. (2007) determined that the KAF typically removes 85–90% arsenic, 90–95% iron, 80–95% turbidity, and 85–99% total coliforms. Similar arsenic removal results have been reported in far western Nepal by the Rural Village Water Resources Management Project (2013) and in central Cambodia by Uy *et al* (2009).

However, the chemistry of the influent water can affect removal. Hard water can cause scaling which prevents rust from forming on the iron. Preferential adsorption by other ions (such as phosphate) can fill up the available adsorption sites on the iron oxide.

Other alternative designs

Numerous situations arise in the 55 countries where the BSF has been employed, which affect the feasibility of BSF design. Several different versions of the BSF have been proposed as a result of different contexts for implementation. The versions suggested are intended to improve feasibility such as reduced weight, less expensive, easier to transport, possible to import, or simpler to make. The suggested materials for the BSF body include cast concrete, injection-molded plastic, PVC pipe, sheet metal, concrete pipe, molded plastic bag, ceramic container, large plastic drum, and 20 L plastic bucket. The shape may be square or round in cross section. Some filters are tapered to improve fabrication or transportation.

An example is the sandstorm BSF from Ethiopia (Smith 2013). The filter has a simple constant head device that provides a much lower head (7 cm) which remains constant throughout much of the filtration cycle. The filter body is made with a cylindrical shell of galvanized iron sheet cast into a concrete base.

Summary

1. The adaptation of slow sand filter (SSF) technology to a point-of-use intermittent slow SSF (the biosand filter (BSF)), has high potential to be an important and significant contribution to water treatment globally. The technology is most applicable to households and institutions without piped water.
2. The design dimensions of the BSF were changed in 2009 based on compelling research that found that the contaminant removal effectiveness of the BSF could be significantly improved at little or no additional cost. This new design (v10) is strongly recommended to new and existing implementers of BSF projects.

3. The specifications for filtration rate of 400 L/hour per m2 and for the filtration sand (effective size = 0.15 to 0.20 mm and uniformity coefficient = 1.5 to 2.5) have been carefully selected to balance the reliability of the BSF as an effective water treatment with the needs of the users.
4. The intermittent flow of the BSF means that there is a pause period between filtration runs. Research has found that longer pause periods are generally better for contaminant removal effectiveness. Further research is needed to quantify the effects and optimal length of the pause period.
5. The BSF is small enough to allow cleaning by hand, eliminating the need to remove or replace sand. The user is able to operate and maintain the filter him/herself.
6. Based on field evaluations, the diffuser basin is preferred over a diffuser plate. The number of holes and their diameter has been the topic of two studies resulting in new learning. An injection-molded diffuser basin has been developed which has substantial advantages over other options.
7. BSFs amended with iron have been found to enhance virus, bacteria, and arsenic removal (in comparison with the sand-only BSF).

Conclusion

The simplicity, high user satisfaction, and sustainability of the biosand filter (BSF) have resulted in increasing research interest in BSF technology. Research and development has led to further performance improvements, making the BSF even more attractive for wider adoption. Considering the majority of the nearly 800 million people lacking access to improved water are rural households (WHO and UNICEF 2013) where conventional, large-scale, drinking water treatment plants are often inappropriate, there is significant potential for the BSF to play a more prominent role in providing safe water. Therefore, further research of the technology should be encouraged.

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