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Sandstorm: a biosand filter designed for small-scale enterprises

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Compared to popular concrete biosand filter designs the Sandstorm biosand filter presented here claims to be lighter, cheaper, faster to make and requires no special tooling or molds. Tested in realistic field conditions in Ethiopia alongside popular concrete biosand filters Sandstorm delivers higher bacteriological removal efficiencies and larger water volumes. Though particularly relevant for implementation in a low-technology, small-scale enterprise model, the design also offers significant scale-up advantages for larger scale implementers due to the advantages of manufacturing speed and transportability. The innovative design follows a partnership between Tearfund UK and Desert Rose Consultancy in Ethiopia.

Concrete biosand filter background

The concrete biosand filter (CBSF) has been used in Ethiopia for over 15 years. The popularity of this design stems primarily from a long-standing co-operation between The Centre for Affordable Water and Sanitation Technology (CAWST), Samaritan's Purse (SP), and The Ethiopian Kale Heywet Church (EKHC), an active local partner behind the fabrication and distribution of over 16,000 filters since it was introduced in 1997 (EKHC 2013). Unlike plastic models, the CBSF offers a robust durable design whose manufacture has proved quite feasible in low-technology environments in which it is frequently used.

It is over 20 years since the intermittently operated CBSF was first designed and tested as a household water treatment option (Buzunis 1995). In this time a large body of academic research and field experience of the CBSF has led to further optimisation of a number of parameters. Research on key parameters affecting the pathogenic removal efficiency are numerous and include research on head (Jenkins 2009), residence-ratio (Elliot et al 2008), and pause time (Jenkins 2009, Baumgartner et al. 2007).

CAWST consider it their role to collate and disseminate this information worldwide (www.cawst.org) and make sure that the design always stays abreast of current academic research. The evolution of the CBSF from the "version 8" to the version 9 (Figure 1) and most recently the version 10 have all been guided by a collation of academic research and field experience (CAWST 2008).

CAWST have not only changed design parameters in response to research and field experience, but also usage parameters which significantly impact the performance of the CBSF in the home. In particular the frequency of use (Baumgartner et al. 2007) and the technique and frequency of cleaning (Ngai et al. 2012) have been shown to have significant impact on performance.

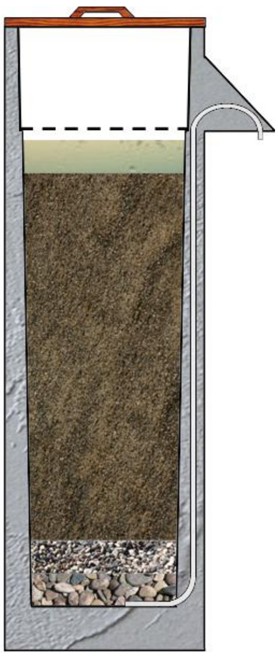

Figure 1. CAWST v9 Concrete biosand filter

The status quo of CBSF design parameters

Recent important recent research-guided evolutions of CBSF design and use can be summarised as follows:

- **Head:** The height of the water responsible for pushing water through the filter is defined as “head”. In a conventional BSF the maximum head (immediately after filling) reduces exponentially as the water runs through the filter. Research shows that, all other things equal, lower heads give lower flows, which deliver higher pathogenic removal rates (Jenkins 2009). Low flows enhance the statistical likelihood of pathogens adhering to a sand particle, or becoming trapped between adjacent particles (ibid). CAWST reduced the head from 27cm (CAWST v9) to 17cm (CAWST v10).
- **Residence ratio:** The volume of water which can be poured at once into the filter divided by the volume of water that can be stored in the pore volume of the sand is called “residence ratio”. Research shows that by changing the residence ratio from 1 to 0.6, the Log Reduction in *E. coli* improves by at least 0.5 whatever the age of the filter (Elliott et al. 2008). In the case of viruses, the most significant improvement is seen by reducing the residence ratio from 0.8 to 0.6 (ibid). This research prompted CAWST to change in residence ratio from roughly 2.0 (CAWSTv9) to 1.0 (CAWST v10). Unfortunately, the same research (ibid) does not indicate any significant performance improvements until the residence ratio is decreased significantly below 1.0.
- **Pause time:** The fact that it should be “intermittently operated” was a key design feature of the original BSF (Buzunis 1995). Research has showed that the time in between uses (fills) is critical to the performance of the BSF (Baumgartner et al. 2007). The same research led CAWST to recommend a pause time of between 6-12 hours because to fill any more frequently would be to the detriment of water quality. Even this might be considered a compromise to an ideal of 24 hours, since some research shows that “BSF performance was best when less than one pore volume...was charged to the filter per day.”(Elliott et al. 2008).
- **Fill volume:** The amount of water that can be poured into a BSF in one operation is called the fill volume. The implication of the optimisations of residence ratio (above) in the CAWST v10 filter meant a reduction of the fill volume from 18.5L to 12.5L.

The status quo of CBSF performance parameters

- **Water quality:** CAWST's research of 16 large-scale BSF projects worldwide puts the average field removal rate at 90% (1 Log) when output water is spot sampled (Ngai et al. 2012).

  This could be considered inadequate. Although any bacteriological removal at all could be expected to deliver at least marginal health benefits, WHO's guidelines for evaluating household water treatment (HWT) options suggest that in the absence of specific data concerning local water qualities, removal rates of Log 2 (99%) for both Bacteria and Protozoa are required before a HWT technology can be judged to be “Protective” at all (WHO 2011). Field performance of a typical CBSF is arguably a long way from this.

- **Water quantity:** The CAWST version 10 delivers about 25L of drinking water per day assuming a conservative pause time of 12 hours is observed to maximise water quality.

  It can be argued that the latest design of CBSF (the CAWST v10) does not deliver enough water. EKHC, who have implemented over 16,000 CBSFs in Ethiopian households assume a family size of 7 (Earwaker 2006). WHO cite 4Lpcd as a bare minimum 'survival' allocation of drinking water (WHO 2005). Thus the CAWST v10 supplies merely 86% of a 'survival' drinking water allocation for 7 people (28Lpcd). The danger of any significant shortfall is that users are tempted to fill more often, resulting in poorer water quality and diminished health benefits.

- **Weight/size:** Currently, the latest CAWST model of CBSF is square, weighs about 95kg (CAWST 2009), is 91.5cm high, and has a maximum width of 42cm (measured diagonally from corner to corner). Experience around the world has shown that typically it takes 4 persons to move either a CBSF or its steel mould any significant distance. Worldwide, the vast majority of CBSFs are implemented by international organisations with access to mechanised transport as well as a significant transport budget. However, in the context of the small-scale rural enterprise model where animal transport is the only option for transport, the weight of both the filter and the mould has proved problematic (Smith 2011).

The end of the road for further optimisation?

In summary, the design and performance parameters are related as follows:

- **Water quality** is a function of *pause time*, *residence ratio* and *head*
- **Water quantity** is a function of *fill volume* and *pause time*
- **Weight** of the empty filter is roughly a function of *filter height* and *cross sectional area* (since the filter is made out of concrete and the wall can be made no thinner without cracking)

This paper therefore argues that modifications to any combination of design parameters for the current design of CBSF would have unacceptable effects on the *weight* of the filter, the *quality* or the *quantity* of water yielded. The following statements (and their converse) demonstrate this:

- Lowering the *head* improves quality but decreases *quantity*.
- Increasing either the *filter height* or *cross-sectional area* gives opportunity for better *residence ratio* (and therefore *quality*) without reducing quantity, but both make the filter even heaver.
- Increasing *pause time* would improve quality but decrease *quantity*.

It is further argued that without fundamental design changes which change the structure of the optimisation problem there can be no truly significant further optimisations. In short, the optimisation problem as it stands is gridlocked by the constraints of *quality*, *quantity* and *weight*.

Sandstorm

Sandstorm presents a new design paradigm that offers a new lease of life to further optimisations as academic research on the designs proceeds. An initial prototype (Sandstorm 1) is presented here merely to demonstrate, with data, the step change in performance that the paradigm offers.

Whereas with the CBSF it was appearing impossible to deliver significant simultaneous improvements in *quality*, *quantity* and *weight*, Sandstorm achieves precisely this through three main innovations, which cascade other benefits:

1. A very simple constant head device which is low-cost (estimated 0.5 USD)
2. A much lower head (7 cm) which remains constant throughout much of the filtration cycle
3. A tank made of a cylindrical shell of 28 gauge galvanised iron sheet cast into a stable base of concrete (Fig. 3)

Constant low head device

A reservoir (inverted 20L jerrican) on top of the filter charges the filter until the working head (Fig. 2) is achieved. Once the water level blocks air from entering the reservoir, charging ceases momentarily. Charging resumes when the water level falls, again allowing air into the reservoir. This cycle maintains the working head for the majority of the filtration cycle.

The constant head device has several benefits; it enables a lower *head* without reducing the total *quantity* of water filtered (Fig 5). Secondly, implementing the water reservoir outside the water filter body enables more space inside for sand, which lowers the *residence ratio*. Thirdly, the large spike in volumetric flow at the beginning of the filtration cycle is smaller (Fig 6). Both a lower *head* and a lower *residence ratio* contribute to the observed improvement in *quality* (Fig 4).

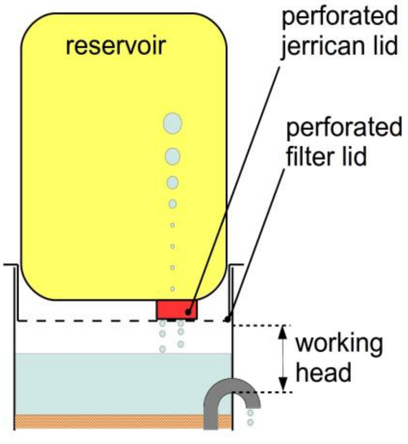

Figure 2. Constant head device

Cylindrical galvanised iron shell

With a CBSF, much of the internal volume is occupied by wall thickness. Galvanised iron (GI) offers a cheap, durable thin wall, which maximises the volume available for filter medium. Making the filter cylindrical (Fig. 3) maximises the volume for any given surface area of material. Since *sand volume* plays a significant role in *residence ratio* this change translates to improved quality. The GI model does not require more sand compared to the concrete filter, though it has 1.5 times the sand volume for filtering. The increase in sand required for media is offset by a reduction in sand needed for concrete.

Figure 3. Sandstorm 1 design

Setting the GI shell in a base of concrete (Fig. 3) was found to be a simple and durable way to seal the bottom of the filter without complex joints. The wider circular base provides extra stability for the filter while also making it simpler to transport and manoeuver into position before filling with sand.

Testing methodology

The performance of an initial prototype (Sandstorm 1) was assessed against CAWST v10 and the more prevalent CAWST v9 in challenging field-like conditions. All filters were filled twice per day at 12 hour intervals for 6 weeks with a mix of local surface and groundwater with a naturally varying pathogen load of 50-150 *E. coli*/100ml.[1] Water was collected, transported and poured by a non-expert member of the local community to simulate real use conditions. To avoid spills contaminating the output water, the output spout was connected by a sealed hose to a collection container. After the full charge of water had run through the filter the collected output was homogenised by shaking the collection container before testing[2]. Samples were drawn from a "Luer lock" sealed with epoxy resin into the container[3]. Samples were drawn and ejected into the vacuum flask using sterilised syringes. After drawing the sample through a Cellulose Acetate Membrane (0.45μm pore size) using a Del Agua vacuum filter, the membrane was placed in a 3M Petrifilm *E. coli* & Coliform Count Plate and incubated at 44ºC. All plates were counted after 18 hours as per 3M guidance notes, and scanned to a digital file on a scanner for a full record.

Performance comparisons

Fig. 4 compares the bacteriological performance[4] of the tested filters. The results show not only more consistency from Sandstorm but also significantly higher average *E. Coli* removal efficiencies.

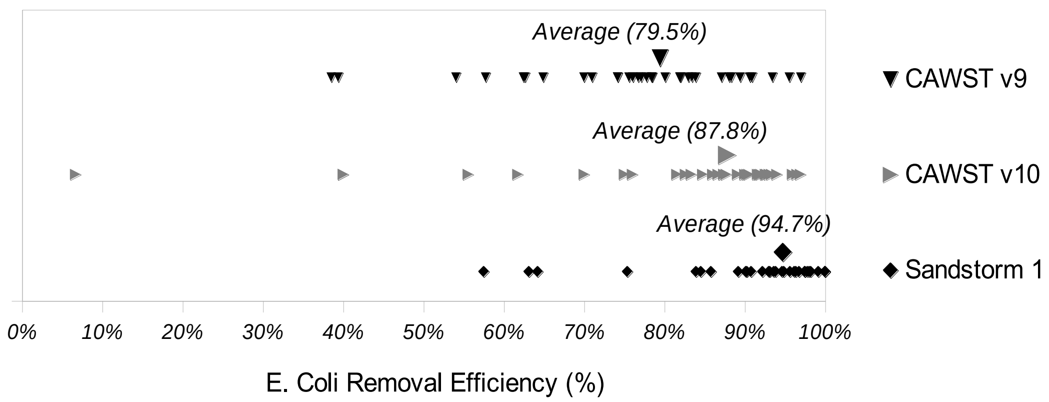

Figure 4. *E. Coli* Removal Efficiency for the tested BSFs

1 This *E. Coli* concentration was chosen to match river water concentrations sampled in March 2013

2 This accurately represents what the user drinks, but is more stringent than the common practice of taking a spot sample from the first 50% of output water which is better quality (Baumgartner 2007).

3 This was done to reduce risks of contamination / spills introduced by sampling the output water.

4 Averages shown are calculated as [1 – (Total *E. Coli* Output Load / Total *E. Coli* Input Load)] for the duration of the trials. An alternative statistically valid way to calculate average values while minimising the effects of outliers is to use the 'median' which yields almost identical values.

As Figs. 5 & 6 show, the constant head device simultaneously delivers lower maximum volumetric flows (measured in m^3/m^2/hour) and large delivery volume. In fact the peak flows exhibited by Sandstorm 1 are half those of the CAWSTv10 and less than 1/6th that of CAWSTv9. This slow and stable flow for the full duration of the filtration run is likely responsible for the water quality improvements observed above.

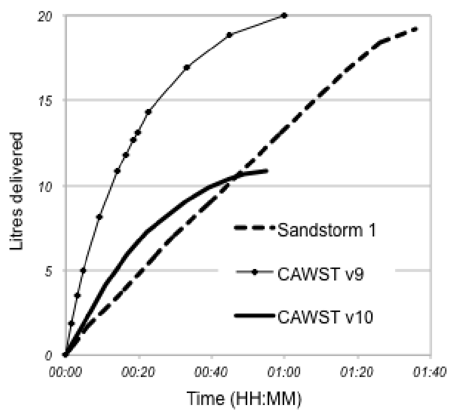

Figure 5. Volume delivery comparison

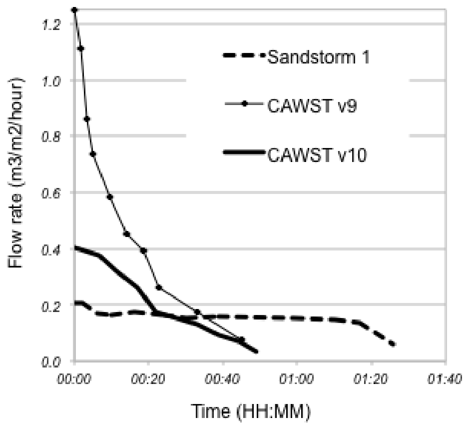

Figure 6. WEDC - Figure title

Table 1. Summarised comparison data for some key design and performance parameters for the tested BSF filters

	Removal efficiency (%)	Water Quantity per day	Empty Weight	Residence ratio	Maximum head	Sand cross sectional area	Width (diagonal or diameter)	Material cost	Tooling cost (±30%)	Manufacture rate / day
Sandstorm 1	94.7%	40L	23 kg	≈1	7 cm	804 cm^2	38 cm	<17 USD	$280	5-10
CAWST v10	87.8%	25L	95 kg	≈1	17 cm	576 cm^2	42 cm	<20 USD	$1000	1
CAWST v9	79.5%	40L	85 kg	2.1	27 cm	576 cm^2	48 cm	<20 USD	$1000	1

Performance in small-scale enterprise

Sandstorm paradigm offers some advantages where the chosen implementation model is through small-scale enterprise in a rural and/or developing context:

Tooling cost is roughly 20% that of the CBSF. Therefore, setup costs are lower as are the tooling costs that the enterprise is passing onto the customer (assuming a full repayment model).

Manufacturing rate of 5-10 times faster than a CBSF. This gives potential to satisfy customers through high demand periods (e.g. harvest time). Costs are thus amortised over a larger number of units making them cheaper for the end user and/or a more profitable enterprise.

Figure 7. Sandstorm 1 weighs 23kg

Weight is ¼ that of a CBSF. At 23kg, most men can carry two Sandstorm 1 filters (Fig 7), as can a donkey or camel. This enables small-scale manufacturers who lack mechanised transport to economically access customers in a wide catchment area.

Transferrable skill-set. The mould for a CBSF can be used for little else. The tools and skill-set used in cutting, joining and bending GI sheet to form Sandstorm can be utilised in the manufacture of a range of water and health related items including rainwater guttering, items used in hand-washing and water storage.
Durability. Current prototypes are 18 months old. Even when empty, a Sandstorm filter is strong enough to stand on. When filled with sand it resists impacts without damage. One concern has been the potential for corrosion in the area where the water level changes above the sand (where both oxygen and water are present). This could be solved with a replaceable lining extending to below the level of the sand. Monitoring to date has not yet demonstrated this need, but will continue.

Conclusions

- The Sandstorm design paradigm offers a number of benefits both in terms of quantity and quality of water delivered, as well as benefits that are specifically relevant to a small-scale enterprise model.
- Most of the benefits have potential to translate directly into higher community impact.
- At the very least Sandstorm offers a high performance alternative to the more widespread CBSF.
- Further research is necessary to understand how best to further optimise the design.
- delivered, as well as benefits that are specifically relevant to a small-scale enterprise model.
- Continuing work will demonstrate performance in implementation and offer learning for scale-up

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