Evaluation of a multi-barrier household system as an alternative to surface water treatment with microbiological risks

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Abstract

Household Water Treatment and Safe Storage (HWTS) are recommended to supply the demand for drinking water in communities without conventional water supply systems. However, there is a lack of long-term laboratory studies regarding such technologies. We evaluated the contributions of each step of a multi-barrier system with pretreatment (sedimentation and fabric filtration), filtration in Household Slow Sand Filters (HSSFs) and disinfection (sodium hypochlorite) treating surface water for more than 14 consecutive months. Removal of turbidity, colour, organic matter, coliform group bacteria and protozoa were evaluated. Two HSSF models were compared, one with a diffuser vessel (HSSF-d) and one with a gravity float equipped vessel (HSSF-f). Correlations between efficiency and operational parameters were assessed. Overall, the multi-barrier system removed more than 90% of turbidity and more than 3.5 log of *Escherichia coli*. HSSF removed up to 3.0 log of *Giardia* spp. and 2.4 log of

Cryptosporidium spp.. HSSF-f presented significantly higher removal rates for turbidity, apparent colour and *E. coli*. Disinfection resulted in water with *E. coli* concentration lower than 1 CFU $100mL^{-1}$, however it was not able to inactivate protozoa. The evaluated system was able to reduce microbiological risks from water and could indeed be an alternative to communities that depend on surface water as their main source of supply. Nevertheless, further studies are recommended to include a low-cost disinfectant for protozoa inactivation.

Keywords: household water treatment, slow sand filtration, biosand filter, drinking water, rural communities.

Abbreviations:

HSSF: Household Slow Sand Filter

HSSF-d: Household Slow Sand Filter equipped with a diffuser

HSSF-f: Household Slow Sand Filter equipped with a float valve

MDI: Morrill Dispersion Index

MFR: Maximum Filtration Rate

PVC: Polyvinyl chloride

SS: suspended solids

1. Introduction

A lack of or limited access to safe, nearby and continuous water sources affects 785 million people worldwide (WHO and UNICEF 2019). Unsafe water consumption is related to 502 thousand deaths every year due to diarrhoeal diseases (Troeger et al. 2017). Household water treatment systems are small scale alternatives able to supply safe drinking water to families without access to it. Furthermore, the World Health Organization (WHO) recommends the use of multiple barriers to increase water safety in communities isolated from a centralised water treatment and distribution system (WHO 2017).

Household treatments need to be able to provide safe drinking water in quantity and quality at a relatively low-cost with simple operation (Sobsey et al. 2008). Among the available alternatives, Household Slow Sand Filters (HSSFs) play a leading role (Hunter 2009; Sobsey et al. 2008). HSSFs were first proposed in the early 1990s and, different from conventional sand filters, can be operated intermittently (CAWST, 2009). The characteristic that enables the HSSF to operate intermittently is the minimum water level above the sand layer, which allows the development of an aerobic biolayer at the sand-water interface (CAWST, 2009). Particle accumulation and microbiological development results in the formation of the *schmutzdecke* (Elliott et al. 2008). As the *schmutzdecke* develops (maturation), sand pore size is reduced, decreasing filtration rate and increasing mechanical trapping of impurities*, i.e.,* increasing HSSF efficiency (Kennedy et al. 2012).

Household slow sand filters are able to treat water containing particulate material, organic matter, chemical compounds, bacteria, viruses, cyanobacteria and protozoa (Adeyemo et al. 2015; Elliott et al. 2008; Jenkins et al. 2011; Palmateer et al. 1999; Sabogal-Paz et al. 2020; Terin and Sabogal-Paz 2019). Despite the promising results, improvements to this technology are still needed. Among the issues that require attention are the limited efficiency of HSSFs treating high turbidity waters and during the maturation period (CAWST, 2009). Furthermore, regarding protozoa in particular, limited information is available in the literature. After Palmateer et al. (1999) reported removals of at least 3.9 log and 5.0 log for *Giardia* and *Cryptosporidium*, respectively, little attention was given to this subject. More recent studies, however, have shown that the HSSF's efficiency removing such pathogens may not be as high as previously reported (Adeyemo et al., 2015; Andreoli and Sabogal-Paz, 2020; Freitas et al., 2021; Medeiros et al., 2020; Napotnik et al., 2020).

In this scenario, we evaluated an easy-to-implement multiple-barrier water treatment system, submitted to contaminated surface water in a long-term operation (442 days). The first system barrier was a pretreatment by sedimentation and fabric filtration, aimed to reduce HSSF influent water turbidity. The second was the household slow sand filtration, comparing two novel HSSF models. Both models were made of PVC, considered easier to construct than the concrete HSSFs, and one of the models was modified to reduce the filtration rate aiming to increase HSSF efficiency, especially during the maturation period. Finally, the last barrier was disinfection by sodium hypochlorite (NaOCl).

To the best of the author's knowledge, there is no published laboratory study of a similar system. Furthermore, this is the longest laboratory study evaluating intermittent HSSF treating natural surface waters. Additionally, we expanded the knowledge on protozoa removal by HSSF, a subject that has limited information in the literature.

2. Methodology

2.1. Raw water and pretreatment

Raw water was collected from the Monjolinho River (São Carlos, Brazil) and it was pumped daily to an elevated 500 L water reservoir. Pretreatment consisted of 24-hour sedimentation followed by a passage through two layers of a non-woven synthetic fabric (100% polyester, 2 mm thickness and ± 0.2 g cm^{-3} specific gravity). Synthetic fabric was positioned at the opening of a 200 L water tank, where the pretreated water was stored.

2.2. Household slow sand filter (HSSF)

2.2.1. Structure

Two intermittent Household Slow Sand Filter (HSSFs) models, with their replicas, were evaluated (four filters in total), using the model described in Terin and Sabogal-Paz (2019) with adaptations. HSSFs were built using PVC pipes and PVC fittings (cross-section area = 0.053 m^2). One model (HSSF-d) was equipped with a diffuser vessel: a 13.6 L bucket with four 1.5 mm holes in its bottom. The other model (HSSF-f) was equipped with a vessel able to limit the maximum water level within the filter, instead of a diffuser: a 20.0 L bucket with a single hole in the bottom, to which a float valve (for gravity water filter) was installed. HSSF-f was designed so that the float valve would close itself when the water level above filtration layer (hydraulic head) reached approximately 15 cm, slowing water going into the filter (*i.e.*, the maximum filtration rate was limited). Six piezometers were installed in each filter, at different heights, to measure head loss through filter media. The filter schemes are shown in Figure 1.

[Figure 1 near here]

Filters were filled with material bought at local hardware stores and gardening centres, which were previously washed, sun-dried and sieved. The support layer consisted of 7.5 cm of coarse gravel (bottom) and 5 cm of fine gravel (top). Above it there was a 5 cm separation layer of coarse sand and, finally, the 50 cm filtration media layer. Filtration media consisted of fine sand with an effective size (d_{10}) of 0.17 mm and uniformity coefficient (UC) of 2.3 (Table S1, supplementary material). A layer of the same synthetic fabric used in the pretreatment was positioned at the top of the filtration layer and fixed using a PVC ring. The synthetic fabric was used to improve the filter efficiency, as it may act as a support to *schmutzdecke* development and help maintenance (Maciel and Sabogal-Paz 2020). The filter charging volume was determined based on the volume which could be occupied by water within the filter: 16 L (Table S2 - supplementary material).

2.2.2. Tracer tests

Tracer tests were performed in order to characterise HSSF-d and HSSF-f flow patterns. Sodium Chloride (NaCl) was used as a tracer and tests were performed in triplicate for each filter unit. In each test, two 16 L feeds of 100 mg L^{-1} NaCl solution were poured into the filters, followed by well water feeds (enough to remove all NaCl from the filters). The interval between feeds was the time required to filter 16 L, which was previously determined to be, on average, 2h 20 min. A conductivity probe (*Vernier Software & Technology*, USA) was positioned at the end of the HSSFs outlet tube to measure the filtered water conductivity (one measurement per minute). The conductivity probe was calibrated beforehand to correlate conductivity with tracer concentration. The data was collected and recorded by the Logger Lite software (*Vernier Software & Technology*, USA).

2.2.3. Filtration rate tests

Filtration rate tests were performed in order to characterise the filter maximum filtration rate (MFR), time to reach MFR and total filtration time. Filtration rate tests were made in triplicate by feeding the filters with well water and measuring the filtered volume minute by minute. Total filtration time was used to calculate pause periods, which are when the water remains undisturbed within the filter, equals to the time between feeds minus the total filtration time.

2.2.4. Operation

Clarified water inside a 200 L water tank was pumped into buckets and fed to the filters. Filters were fed 3 times a day: at 8:00 am, 1:00 pm and 6:00 pm. Charging intervals resulted in two distinct pause periods. Each filter produced 48 L day^{-1}, considered enough to provide the minimum daily requirements to a family of up to 6 people (Howard and Bartram 2003). All filtered water was collected in 50 L water tanks, from which samples were taken. After collecting the samples, the water tanks were washed. The samples were analysed according to Table 1.

[Table 1 near here]

Giardia spp. cysts and *Cryptosporidium* spp. oocysts were inoculated directly into the filters daily for 112 days after the 330th day of operation. The number of cysts and oocysts inoculated daily was, approximately, 10^3 and 10^2, respectively. *Giardia* spp. cyst and *Cryptosporidium* spp. oocyst quantification methodologies are presented in Item 2.4.

2.2.5. Maintenance

HSSF maintenance was performed when the filters were unable to produce 48 L day^{-1}. Simplified maintenance was made by moving the synthetic fabric above filtration layer.

After doing this, the filtration rate was restored with a minimum impact over the *schmutzdecke*. When simplified maintenance was not enough, a complete maintenance was performed. Complete maintenance consisted of removing and washing the synthetic fabric and cleaning the sand first centimetres by stirring, adapted from the methodologies presented by Singer et al. (2017). Well water was used in maintenance. After sand cleaning, the synthetic fabric was repositioned and filters were fed with water, which was discarded once filtered.

2.3. Disinfection

Sodium Hypochlorite (NaOCl) was used to disinfect filtered water due to its simplicity, easy access and low cost. NaOCl dosage was initially determined in bench tests, in triplicate. Filtered water disinfection started on the 307th day of operation. Daily, after filtered water samples were collected, NaOCl was added to the filtered water tanks and homogenised for 1.0 min. After 30 min contact time, disinfected water samples were collected. Sodium Metabisulfite was used to neutralise residual chlorine. Disinfected water samples were analysed identically as filtered water samples (Table 1) and for residual chlorine, *Giardia* spp. cysts and *Cryptosporidium* spp. oocysts according to Item 2.4.

2.4. Analyses

All water samples were analysed according to Table 1. Regarding protozoa protocol, *Giardia* spp. cysts and *Cryptosporidium* spp. oocysts were quantified in filtered and disinfected water using concentration by membrane filtration (Franco et al. 2001) followed by immunofluorescence microscopy detection using the Merifluor® kit (*Meridian Bioscience Diagnostics*, USA). Protozoa wall integrity was analysed as a proxy for protozoa viability using Propidium Iodide dye. Analytical quality tests using ColorSeed® (*TCS Bioscience*, United Kingdom) were performed.

Measures of MFR and head loss were done daily in the HSSFs, 15 minutes after the first water feed of the day. Furthermore, total chlorine and free chlorine were quantified in disinfected water, three times a week, adopting HACH method 8021 using DPD total chlorine and free chlorine reagent powder pillows, respectively (*HACH*, USA).

After the operation, *schmutzdecke* samples from the blanket and the first centimetres of sand were collected and analysed for suspended solids (SS) (APHA et al. 2012) and for morphological identification of microorganisms by bright field microscopy (*Olympus* ® *BX60*, Japan). Furthermore, synthetic fabric was analysed by scanning electron microscopy (SEM) (*Zeiss® LEO 440*, Germany) before and after operation.

2.5. Data analysis

Duplicates of each model were evaluated in order to obtain a more representative picture of the HSSF performances. Hence, the data from HSSF-d and HSSF-f were analysed based on the mean values from both units of each model and are presented as such, unless otherwise indicated.

Some of the obtained results were divided into two groups and analysed based on seasonality. The so-called *dry season* comprehended the periods from May 2018 to July 2018 and from April 2019 to July 2019; while the so-called *rainy season* comprehended the period from August 2018 to March 2019. The groups were determined based on the rainfall data from the Brazilian National Institute of Meteorology (INMET). Differences between seasons could affect HSSF efficiency, for instance, during the dry season, raw water presented lower turbidity and the temperatures were lower when compared to the rainy season.

Regarding statistical analysis, normality tests were performed to determine dataset distribution and, subsequently, the most suitable type of statistical tests. To determine if two datasets were significantly different from each other, the T-test was used for normal independent datasets, the Mann-Whitney test was used for non-normal independent datasets, the paired T-test was used for normal dependent datasets and the Wilcoxon test was used for non-normal dependent datasets. All previously mentioned tests considered a significance level of 5%. The Spearman correlation test (non-parametric) was used to determine correlation between two datasets, within a 5% significance level. Correlation was considered significant when the p-value < 0.05 and the module of Spearman coefficient (r_s) was greater than the module of critical r_s. All statistical analyses were performed using PAST software (Hammer et al. 2001).

3. Results and discussion

3.1. Tracer tests

HSSF-d and HSSF-f presented the Morrill Dispersion Index (MDI) of 2.2 ± 0.0 and 2.6 ± 0.1, respectively. Neither the models presented MDI below 2, considered effective plug-flow by the US Environmental Protection Agency (USEPA) (USEPA 1986). The mean MDI for both models was also higher than values reported for intermittent HSSF, which can vary from 1.3 to 1.9 (Elliott et al. 2008; Kennedy et al. 2013; Terin and Sabogal-Paz 2019). However, MDI varies from 1 (ideal plug-flow) to 22 (ideal complete-mix) (USEPA 1986). Hence, HSSF-d and HSSF-f presented flow patterns considerably closer to the ideal plug-flow. Figure S2 (supplementary material) shows the curves of tracer concentration *versus* the fed volumes filtered. Overall, the 4 filters (2 HSSF-d and 2 HSSF-f) showed similar curves, with the tracer starting to come out of the filters shortly before 1 feed was filtered and reaching the maximum concentration between the filtration of 2 and 3 feed volumes. After that, tracer concentration drops to zero before 4 fed volumes were filtered. The sharp increase and decrease of tracer concentrations are characteristic of a plug-flow reactor (Elliott et al. 2008; Kennedy et al. 2013). A flow regime closer to ideal plug-flow indicates the reduced effect of dispersion by tortuous flow paths, therefore, all portions of water had an equivalent time within the filter (Elliott et al. 2008; Sabogal-Paz et al., 2020). Furthermore, a plug-flow regime favours microbiological processes, potentially improving HSSF efficiency (Ballyk and Smith, 1999; Souza Freitas and Sabogal-Paz, 2020).

3.2. Maximum filtration rate (MFR)

Tests with clean sand showed that 15 minutes was the mean time required for the HSSF to reach its MFR. Mean clean sand MRFs were 12.0 ± 0.8 m^3 m^{-2} day^{-1} and 9.0 ± 0.3 m^3 m^{-2} day^{-1} for HSSF-d and HSSF-f, respectively. In intermittent operation, the filtration rate reaches its maximum a few minutes after water is poured into the filters and then reduces with the reduction of the hydraulic head, until the hydraulic head reaches its minimum (approximately 5 cm). Filtration rate profiles during filtration runs in clean sand are presented in Figure S3 (supplementary material). Selected diffuser layout resulted in an HSSF-d mean clean sand MFR above CAWST (2009) recommendations of 9.6 m^3 m^{-2} day^{-1}. However, over operation time, as the *schmutzdecke* develops, so does the head loss, decreasing the filtration rate.

The float valve in HSSF-f kept the maximum hydraulic head constant and, consequently, the filtration at clean sand MFR lasted longer than in HSSF-d, which presented a higher clean sand MFR (Figure S3 - supplementary material). As a result, both filters required approximately 2 hours and 20 minutes to filter 16 L and, consequently, presented similar pause periods. Pause periods were 2h 40 min between daily feeds and 11h 40 min overnight. It is important to notice that, over time, the flow rate decreases and with it the pause period decreases. However, in this case, the maturation and the lower filtration rates compensate the reduction in the pause period regarding filtration efficiency (Elliott et al. 2008; Maciel and Sabogal-Paz 2020).

Filtration rate measures during operation (Figure 2) showed a mean MRF of 5.3 ± 2.3 $m^3 m^{-2} day^{-1}$ for HSSF-d and 2.7 ± 1.7 $m^3 m^{-2} day^{-1}$ for HSSF-f. There was a statistically significant difference between HSSF-d and HSSF-f MRFs (p-value < 0.001). It is noted that the lower hydraulic head and, consequently, lower filtration rate in HSSF-f did not result in the need for more frequent maintenance. HSSF-d presented a significant difference in its MFR when comparing the dry season and rainy season (p-value < 0.001). The same was not observed for HSSF-f (p-value = 0.06). In addition to restraining the MFR, using the float valve resulted in filtration rate equalisation for approximately 30 minutes, as seen in Figure S3. A constant MRF could reflect more stable efficiency, despite seasonality, which could increase the HSSF-f dependability.

[Figure 2 near here]

3.3. Pretreatment

Although performed using large water tanks, due to the requirements to operate four HSSFs simultaneously, pretreatment could be done without complications using a set of buckets in household settings. Characterisation of raw water and pretreated water, pretreatment removal/variation and p-value from Wilcoxon tests are shown in Table 2.

[Table 2 near here]

The number of samples with turbidity higher than 50 and 10 NTU were reduced by 76% and 55%, respectively, after pretreatment. Furthermore, turbidity below 10 NTU, the recommended value for HSSF influent water in countries with more restrictive drinking water standards (Sabogal-Paz et a, 2020), was observed in 66.1% of the pretreated water samples. Additionally, there was a significant removal of total coliforms and *E. coli* that reached 1.2 log, and a significant reduction of particle size.

Spearman's correlation coefficient showed a strong positive correlation between raw water turbidity and pretreated water turbidity (p-value < 0.001). However, there was also a strong positive correlation between raw water turbidity and pretreatment efficiency (p-value < 0.001), indicating that pretreatment system was able to equalise pretreated water turbidity to some extent.

3.4. Household slow sand filters

Mean residual concentrations of the analysed parameters in the filtered water and mean removal rates are presented in Table 3.

[Table 3 near here]

Filtered waters presented a significant removal/variation of most parameters, when compared to pretreated water; except partial and total alkalinity, dissolved oxygen and particle size for HSSF-f, and conductivity for HSSF-d. Furthermore, parameters with different removal rates between filter models were turbidity, *E. coli*, apparent color and pH (Tables S3, supplementary material). It was observed that the results presented an elevated standard deviation (Tables 2 and 3), mostly due to the length of operation and the use of river water.

There was no significant difference between the filters´ DOC removal efficiencies (p-value = 0.18). However, HSSF-d was affected by seasonality, presenting differences in DOC removal rates (p-values = 0.005), while HSSF-f did not (p-value = 0.05). The mean true colour remained below 15 HU for both filter models (WHO 2017). Colour removal by slow sand filtration depends mostly on sedimentation, which, in turn, depends on the filtration rate (Guchi, 2015). In fact, correlations between the filtration rate and remaining colour and colour removal were observed (Table S4, supplementary material). Furthermore, reductions in absorbance (λ 254 nm) were higher than previously reported for intermittent HSSF (Lynn et al. 2013), likely due to the reduction in the filtration rate as well. Besides reducing the colour and taste of the water, organic matter removal by the HSSFs potentially reduces the formation of trihalomethanes, or other health risk related subproducts, during the chlorination step.

3.4.1. Turbidity

Mean turbidity removals were 68.1 ± 18.1% and 69.4 ± 20.7% for HSSF-d and HSSF-f, respectively. Intermittent HSSF turbidity removal efficiencies can range from 78% to 96% (Elliott et al. 2008; Jenkins et al. 2011; Maciel and Sabogal-Paz 2020; Young-Rojanschi and Madramootoo 2014). Removal rates slightly below those previously reported were mostly due to the use of natural unaltered river water, unlike other laboratory studies (Elliott et al. 2008; Jenkins et al. 2011; Maciel and Sabogal-Paz 2020). During the 442 days of operation, peaks in raw water turbidity were observed, reaching 139 UNT. On such days, although the pretreatment reduced influent water turbidity, poor removal rates by the HSSFs were reported, which influenced the overall performance. Nevertheless, filtered water presented mean residual turbidity below the acceptable value of 5 NTU (WHO 2017).

Pretreated water and filtered water turbidity over time are presented in Figure 3. It can be observed that the oscillations in pretreated water influenced filtered waters, especially during the rainy season (Table S5, supplementary material). Additionally, there was a difference in filtered water turbidity between seasons (p-value < 0.001 for both filter models), but not in turbidity removal rates (HSSF-d p-value = 0.33; HSSF-f p-value = 0.75).

[Figure 3 near here]

Remaining turbidity in filtered waters correlated strongly with pretreated water turbidity (p-value < 0.001 for both filter models). In contrast, Napotnik et. al (2017) and Maciel and Sabogal-Paz (2020) did not observe a correlation between influent water and filtered water turbidity (Maciel and Sabogal-Paz 2020; Napotnik et al. 2017). The main reasons could be the lower influent water turbidity range and a shorter duration of experiments in the aforementioned studies. According to Kennedy et al. (2013), influent water quality can affect filtered water quality, as well as biological development within HSSF (Kennedy et al. 2013).

Removal rates correlated strongly with the operation time and MFR (p-value < 0.001 for both filter models), rather than influent turbidity (HSSF-d p-value = 0.04; HSSF-f p-value = 0.05). Turbidity removal and remaining turbidity also correlated with the *schmutzdecke* age (time after maintenance) (Table S6, supplementary material). The same was reported by Maciel and Sabogal-Paz (2020), for remaining turbidity.

The presented results show that *schmutzdecke* development, which is related to the time of operation and MFR, besides the actual *schmutzdecke* age, had a greater influence than influent water quality over the turbidity removal efficiency. Increase in

HSSF efficiency over time is related to *schmutzdecke* development, as it reduces sand pores, increasing particle trapping and decreasing filtration rate, which, in turn, improves the filtration process (Elliott et al. 2008; Kennedy et al. 2013; Tundia et al. 2016).

3.4.2. Total coliforms and *E. coli*

Mean total coliform removal rate was 1.8 ± 0.6 log for both HSSF-d and HSSF-f (p-value = 0.86), reaching 3.3 log. The observed removal rates were higher than previously reported for HSSFs treating surface waters (< 1.5 log) (Baumgartner et al. 2007; Yildiz 2016). Both models presented a stable coliform removal rate, with no significant differences between dry and rainy seasons (Tables S5 and S6, supplementary material). Absence of total coliforms in 100 mL was not observed in the filtered water from neither the HSSF models, however the total coliform presence in drinking water is not directly related to health hazards (WHO 2017). HSSF-d and HSSF-f removal rates for total coliforms and *E. coli* over operational time are presented in Figure 4.

[Figure 4 near here]

Mean *E. coli* removal rates were 1.5 ± 0.7 log for HSSF-d and 1.7 ± 0.8 log for HSSF-f, reaching 2.9 log and 3.6 log for HSSF-d and HSSF-f, respectively. Mean removals were within the expected range for intermittent HSSF (1.3 – 2.9 log) (Elliott et al. 2008; Jenkins et al. 2011; Maciel and Sabogal-Paz 2020; Souza Freitas and Sabogal-Paz 2020; Young-Rojanschi and Madramootoo 2014). However, considering only full-scale HSSFs treating surface waters, *i.e.*, similar conditions to the present study, the proposed HSSF models, especially HSSF-f, presented higher efficiencies than previously reported (Elliott et al. 2008; Jenkins et al. 2011; Stauber et al. 2006). Furthermore, the HSSF-f mean *E. coli* removal was higher than that observed by Maciel and Sabogal-Paz (2020) for an intermittent HSSF with a similar water level control device (1.4 ± 0.6 log) (Maciel and Sabogal-Paz 2020). These authors did not observe any statistical difference between the HSSF model with water control and a HSSF model without it (Maciel and Sabogal-Paz 2020). In the present study, however, there was a significant difference between HSSF-d and HSSF-f *E. coli* removal efficiencies (p-value < 0.001).

Besides the overall operation, a relatively better performance was also observed by HSSF-f during the maturation period when compared to HSSF-d (Figure 4) and to the literature (Elliott et al. 2008; Kennedy et al. 2013). HSSF-f reached 1.0 log mean removal rate on the 16^{th} day of operation, baseline removal established by WHO (WHO 2017), while HSSF-d reached 1.0 log mean removal rate on the 30^{th} day. Better initial results of HSSF-f were attributed to the lower filtration rate, which is related to a reduction of shear forces (facilitating *schmutzdecke* development), as well as increased contact (more exposure to predation and adsorption), and particle sedimentation (Jenkins et al. 2011; Tundia et al. 2016). After day 93 the removal rates were almost always above 1.0 log for both HSSF models, except for off events, mostly after maintenance. Furthermore, HSSF-f presented a more stable behaviour regarding seasonal changes, while HSSF-d *E. coli* removal efficiency significantly changed between seasons. Additionally, absence of *E. coli* in filtered water was observed in 29.1% of HSSF-f samples and in 13.4% of HSSF-d samples.

Filtration rate and time of operation presented strong correlation with *E. coli* removal, regardless of the HSSF model, and both parameters are related to *schmutzdecke* development. Influent concentration of *E. coli* also correlated to HSSF removal efficiencies, as previously reported (Maciel and Sabogal-Paz 2020; Napotnik et al. 2017). Furthermore, HSSF-f presented correlation between *E. coli* removal with *schmutzdecke* age (p-value = 0.02), however, the same was not observed for HSSF-d (p-value = 0.26). Besides the effect of lowering filtration rate, this may be due to the fact that the higher filtration rates in HSSF-d forced *schmutzdecke* microorganisms to greater depths. Thus, the maintenance, in which only the sand first centimetres were cleaned, may not have affected HSSF-d performance as much as it did HSSF-f (Table S6, supplementary material). Head loss analyses (not shown) confirmed a higher presence of material at greater depths in HSSF-d, when compared to HSSF-f.

3.4.3. *Giardia* spp. cysts and *Cryptosporidium* oocysts

The method used was considered suitable for the analysed matrix, since cyst and oocyst recoveries were in accordance with the USEPA Method 1623.1 (USEPA 2012) (Table S9, supplementary material). Mean *Giardia* spp. removal rates were 2.3 ± 0.8 log and 2.9 ± 0.3 for HSSF-d and HSSF-f, respectively; producing water with less than 1 cyst in 2 L. There was no significant difference between the filter models (p-value = 0.12). However, only one *Giardia* spp. cyst was found in HSSF-f samples (after maintenance); on the other hand, more than one *Giardia* spp. cyst was found in multiple HSSF-d samples. Additionally, all HSSF-f removal rates were almost all above the 2 log threshold established by WHO (WHO 2017).

Regarding *Cryptosporidium* spp., the mean removal rates were 0.9 ± 0.4 log and 1.1 ± 0.7 for HSSF-d and HSSF-f, respectively, producing water with less than 1 oocyst per litre. No statistically significant difference was observed between filter models (p-value = 0.45). Inferior *Cryptosporidium* spp. removal rates, when compared to *Giardia* spp., were reported and attributed to the small size of oocysts (4-7 µm, *versus*

8-12 µm of Giardia cysts), which may facilitate its passage through sand pores (Adeyemo et al. 2015; Palmateer et al. 1999). Additionally, *Cryptosporidium* oocysts present the ability to compress itself (Li et al. 1995). Removal rates of *Giardia* spp. cysts and *Cryptosporidium* spp. oocysts by HSSF-d and HSSF-f over time are presented in Figure 5.

[Figure 5 near here]

A minor trend towards increasing *Cryptosporidium* removal was observed in the first 4 tests, especially for HSSF-f. However, in the tests after maintenance, removal efficiencies declined. This decline was also noted for *Giardia* spp. removal efficiency by HSSF-d, although greater oscillation in cyst removal was observed over time, which may indicate that the higher filtration rate in HSSF-d could have forced accumulated cysts through the filter media. The presence of *Giardia* spp. cysts in filtered water and *Giardia* spp. cyst removal rates from HSSF-d correlated with the operation time, inoculation time (time after the start of daily protozoa inoculation) and MFR (Table S10, supplementary material). No correlations were observed between remaining *Giardia* spp., nor removal rates, and the considered parameters for HSSF-f. For remaining *Cryptosporidium* spp. and *Cryptosporidium* spp. removal rates, the only correlation observed was between HSSF-f performance and schmutzdecke age (p-values = 0.02).

Palmateer et al. (1999) obtained mean removal rates of 3.9 log and >5.0 log for *Cryptosporidium* oocysts and *Giardia* cysts, respectively. Removal rates reported by the authors were considerably higher than the ones obtained in the present study. However, it is important to notice that the removal rates calculated in log depend on the number of organisms inoculated to the filter. Palmateer et al. (1999) inoculated 10^5 and 10^6 cysts and oocysts, respectively. In a more recent study, Adeyemo et al. (2015) observed removal rates reaching from 1.1 to 1.3 log for *Cryptosporidium*, and 1.2 to 1.4 log for *Giardia*. These results are closer to the ones obtained in the present study. The authors operated a compact HSSF version with 15 cm filtration layer and flow rates between 0.02 and 0.13 $m^3 m^{-2} day^{-1}$. However, key operational parameters such as *schmutzdecke* maturation, adequate feed volume and pause period were not considered by the authors, assessing only the physical retention of protozoa by passage through sand (Adeyemo et al. 2015). Recently published studies on intermittent HSSFs reported *Giardia* removals between 1.5 and >3.4 log (Andreoli and Sabogal-Paz, 2020), and *Cryptosporidium* removals between 0.5 and 4.8 log (Andreoli and Sabogal-Paz, 2020 Napotnik et al., 2020).

The range in which protozoa removal by intermittent HSSF can vary, considering the presented results and the literature, indicates that although HSSF has great potential to remove cysts and oocysts, more research is needed.

3.5. Disinfection

Bench tests showed that a dosage of 0.9 mg L^{-1} of NaOCl was sufficient to provide the minimum free chlorine residual of 0.5 mg L^{-1} in filtered water (Figure S1, supplementary material), recommended by WHO (WHO 2017). Hence, 1.0 mg L^{-1} was used as an initial dosage. However, coliform tests showed that this combination dosage/contact time was not enough to achieve an acceptable inactivation *E. coli*. Therefore, NaOCl dosage was increased to 2.0 mg L^{-1}, meeting the dosage recommendations by WHO for household chlorine disinfection of clean water (WHO 2017). Residual free chlorine concentrations were the same for both filtered waters (1.4

± 0.4 mg L^{-1}), as was residual total chlorine (1.5 ± 0.4 mg L^{-1}). Residual free chlorine was within the international recommendations of at least 0.2 - 0.5 mg L^{-1} and maximum of 5.0 mg L^{-1} (WHO 2017). The disinfection process resulted in significant variations for most parameters when compared to filtered water, including bacteria, turbidity, color and pH (Table S11 - supplementary material). Mean residual concentrations in the disinfected water and mean removal rates are presented in Table 4. It can be observed that negative variations for absorbance and DOC were not significant (p-value > 0,05).

[Table 4 near here]

Total coliforms and *E. coli* inactivation were considerably low (Table 4). According to WHO, bacteria inactivation by chlorination varies between 3 and 6 log (WHO 2017). The already low concentration of bacteria in filtered water was mainly responsible for these results (Table 3). Absence of *E. coli* was observed in 71.9% and 80.6% of disinfected samples from HSSF-d and HSSF-f, respectively. However, total coliform absence was not obtained. Most samples that still contained *E. coli* after disinfection presented only 1 CFU 100 ml^{-1}, with all samples categorised as low risk (< 10 CFU 100 ml^{-1}) (WHO 2017). Additionally, the residual free chlorine is expected to be able to prevent recontamination for 24h, if the water is stored properly (Wilhelm aet al. 2018).

Finally, protozoa inactivation by chlorination was not significant (Table 4). Resistance of encysted forms of protozoa to chlorine disinfection was previously reported (Adeyemo et al. 2019; Keegan et al. 2008; WHO 2017). Higher concentrations of chlorine could reduce protozoa viability (Adeyemo et al. 2019); however, use of high chlorine concentrations could make water unfit for human consumption.

3.6. *Schmutzdecke* characterisation

Among the observed microorganisms in the sand and synthetic fabric, there were microalgae, protozoa, suspended bacteria, cyanobacteria, worms' eggs and larvae and zooplankton (Table S12, supplementary material). It is worth mentioning that some of the identified microorganisms were reported as able to ingest cysts and oocysts, such as rotifers and ciliate protozoa (Bichai et al. 2014; Stott et al. 2001).

Suspended solids (SS) analyses showed a similar accumulation of particles in HSSF-d and in HSSF-f, 23.1 ± 8.0 g L^{-1} and 24.8 ± 2.9 g L^{-1}, respectively (p-value = 0.65), according to Table S13 (supplementary material). Volatile suspended solids (VSS) only accounted for 3.3% and 3.9% of the total SS content in HSSF-d and HSSF-f, respectively. Hence, inorganic materials were the major constituent of the filters *schmutzdecke*; however, the presence of sand particles in the samples may have been responsible for this difference observed between organic and inorganic content. Nevertheless, particle accumulation is an important part of *schmutzdecke* development (Elliott et al. 2008). There were no significant differences between the SS contents in the sand and synthetic fabric for neither the HSSF models (p-value = 0.7; Mann-Whitney test). Furthermore, the synthetic fabric was able to support more than 50% of the total suspended solids concentration (*schmutzdecke*) (Table S13), indicating its potential to improve HSSF efficiency and ease filter operation (*e.g.,* simpler maintenance).

The differences between the synthetic fabric before and after use were considerable, with the latter presenting regions with intense material accumulation (Figure S5, in supplementary material). Structures similar to the silica scales from freshwater algae *Mallomonas tonsurata* (Karlson et al., 2020) were identified by SEM. Similar organisms are commonly found in cold and oligotrophic water bodies but were also observed in eutrophic water bodies in more tropical regions (Lak Lee et al., 2008). Its blooming can cause a bad taste and odour to potable water; however, this was not the case in the present study. Sand particles were also trapped within the synthetic fabric fibres, probably due to the movement of the fabric during simplified maintenance.

4. Conclusions

The evaluated multi-barrier household water treatment system was able to remove between 91.4% and 90.5% of turbidity and between 3.5 log and 3.8 log of *E. coli*, with HSSF-d and HSSF-f, respectively. Regarding the filtration process, HSSF-d and HSSF-f did not present statistically different performances for most analysed parameters; however, HSSF-f was significantly more efficient removing the key parameters turbidity and *E. coli*, and was slightly better than HSSF-d in other aspects (*e.g.,* it required less maintenance and was less affected by seasonality). *E. coli* and total coliform mean removal rates were higher than previously reported for HSSFs treating natural surface waters. Furthermore, both filter models were able to remove cysts and oocysts from water, reaching 3 log removal of *Giardia* spp. and reaching 1.4 and 2.4 log removal of *Cryptosporidium* spp., with HSSF-d and HSSF-f, respectively. However, protozoa were identified in filtered water, reinforcing the need for a disinfection step after filtration. Sodium hypochlorite disinfection proved to be easy to perform and efficient regarding bacteria inactivation, but not protozoa. The proposed system showed promising results treating surface waters and could be a viable alternative to communities without access to safe drinking water. We recommend further evaluation of low-cost disinfection processes able to inactivate protozoa that, even present in low concentrations, could lead to health risks.

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7. Disclosure statement

The authors hereby declare previous originality check, no conflict of interest and open access to the repository of data used in this paper for scientific purposes.

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Table 1 Water quality parameters.

Parameter	Frequency	Methodology/equipment
Turbidity	Daily[a]	Turbidimeter 2100N (*Hach*, USA)
Apparent colour	Daily[a]	Colorimeter DM-COR (*Digimed*, Brazil)
Temperature	Daily[a]	Mercury thermometer
Escherichia coli	Twice a week	9222 - Membrane filter technique for members of the coliform group (APHA, 2012)
Total coliforms	Twice a week	
pH	Weekly	pHmeter DM20 (*Digimed*, Brazil)
Alkalinity	Weekly	
Total Organic Carbon	Weekly	TOC-L (*Shimadzu*, Japan)
True colour	Weekly	Colorimeter DM-COR (*Digimed*, Brazil)
Absorbance at 254 nm	Weekly	DR5000 spectrophotometer (*Hach*, USA)
Conductivity	Weekly	Electrical conductivity meter DM32 (*Digimed*, Brazil)
Dissolved Oxygen	Weekly	Oximeter DO-5519 (*Lutron Eletronics*, Taiwan)
Zeta potential	Monthly	Zetameter Zetasizer Nano Series ZS90 (*Malvern Panalytical*, United Kingdom)
Particle size	Monthly	

Note: [a] Daily analyses were not performed at weekends and on holidays.

Table 2 Raw water and pretreated water qualities, pretreatment removal/variation rates and p-value for Wilcoxon test.

Parameter	Raw water		Pretreated water		Removal/variation		
	Mean	SD	Mean	SD	Mean	SD	p-value
Turbidity (NTU)	27.1	26.1	13.0	14.3	46.2%	23.4%	<0,001*
Escherichia coli (CFU 100mL^{-1})	912	1263	323	477	0.4 log	0.3 log	<0,001*
Total coliforms (CFU 100mL^{-1})	9437	5616	5094	4199	0.3 log	0.3 log	<0,001*
Apparent color (HU)	79.4	54.7	61.2	43.1	20.9%	19.4%	<0,001*
True color (HU)	32.3	23.6	31.3	21.6	0.5%	25.7%	0,012*
pH	6.9	0.1	7.0	0.1	-1.8%	2.1%	<0,001*
Temperature (ºC)	20.0	2.5	19.9	2.5	0.0	0.1	0,061
Absorbance (λ=254 nm)	0.11	0.06	0.11	0.06	-0.4%	17.7%	0,431
Dissolved Organic Carbon (mg L^{-1})	2.4	0.8	2.0	0.8	12.2%	37.7%	<0,001*
Partial Alkalinity (mg $CaCO_3$ L^{-1})	12.6	1.9	13.4	4.6	-8.7%	37.9%	0,714
Total Alkalinity (mg $CaCO_3$ L^{-1})	18.8	2.3	19.8	6.7	-8.6%	39.0%	0,904
Conductivity (S m^{-1})	49.0	7.6	48.3	7.2	1.2%	4.9%	0,031*
Dissolved Oxygen (mg L^{-1})	7.7	0.5	7.8	0.4	-2.6%	6.4%	0,007*
Zeta potential (mV)	-13.9	15.4	-20.4	1.4	25.4%	91.6%	0,530
Particle size (nm)	476.1	269.1	294.6	83.5	29.4%	26.7%	0,008*

Note: *statistically significant difference (p-value < 0.05).

Table 3 Overall mean values and standard deviations for water quality parameters in filtered water from the household slow sand filters with a diffuser (HSSF-d) and the household slow sand filters with a float valve (HSSF-f).

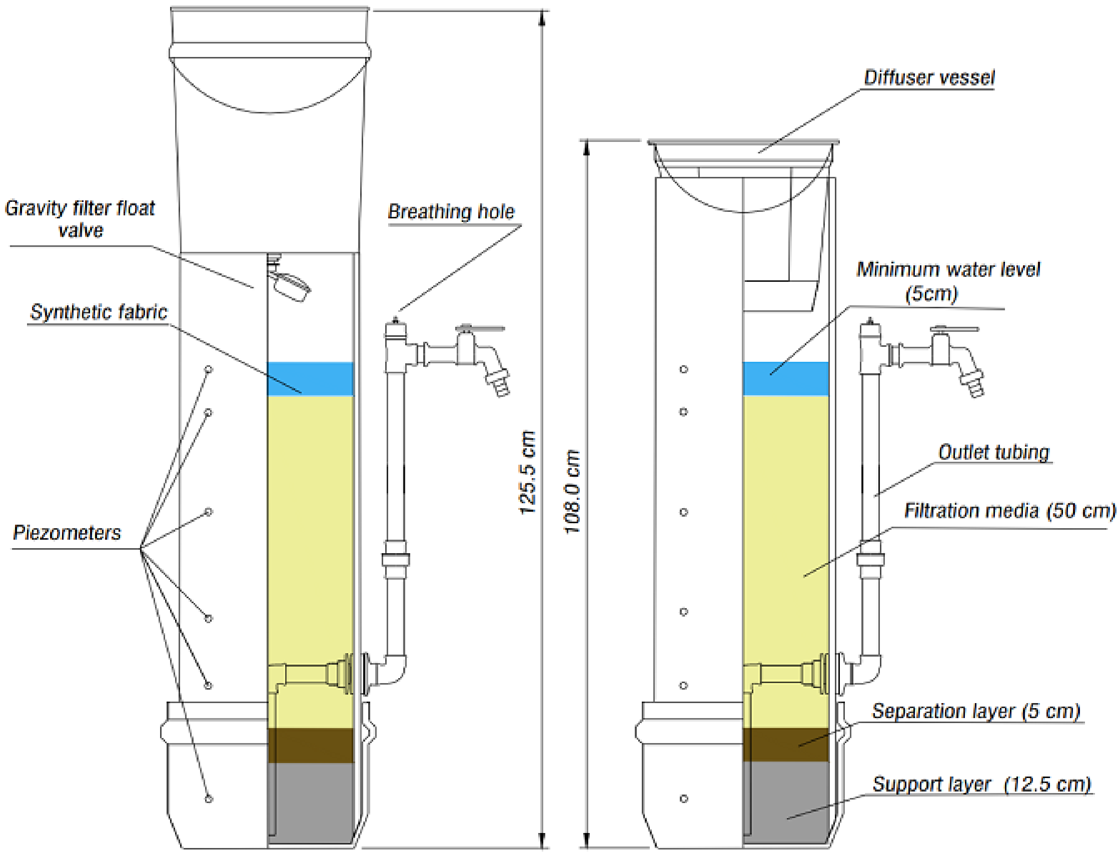
Parameter	HSSF-d		HSSF-f	
	Mean value ± SD	Mean removal/variation ± SD	Mean value ± SD	Mean removal/variation ± SD
Turbidity (NTU)	3.9 ± 5.0	68.1 ± 18.1 %	3.7 ± 4.9	69.4 ± 20.7 %
Escherichia coli (CFU 100mL^{-1})	22 ± 82	1.5 ± 0.7 log	19 ± 84	1.7 ± 0.8 log
Total coliforms (CFU 100mL^{-1})	132 ± 308	1.8 ± 0.6 log	131 ± 322	1.8 ± 0.6 log
Giardia spp. cysts in 48 L	8 ± 12	2.4 ± 0.6 log	0 ± 1	2.9 ± 0.2 log
Cryptosporidium spp. oocysts in 48 L	23 ± 17	1.2 ± 0.4 log	20 ±18	1.4 ± 0.6 log
Apparent colour (HU)	18.7 ± 19.8	71.7 ± 18.6 %	17.6 ± 19.7	73.2 ± 19.7 %
True colour (HU)	12.8 ± 12.4	62.1 ± 21.7 %	12.3 ± 13.4	64.7 ± 22.8 %
pH	7.1 ± 0.1	0.4 ± 9.8 %	7.1 ± 0.1	- 1.1 ± 1.2 %
Temperature (ºC)	20.2 ± 2.5	-1.8 ± 7.4	20.2 ± 2.5	-1.7 ± 7.4
Absorbance (λ=254 nm)	0.06 ± 0.04	48.6 ± 18.4 %	0.05 ± 0.04	51.9 ± 17.7 %
Dissolved Organic Carbon (mg L^{-1})	1.8 ± 0.6	6.4 ± 46.4 %	1.6 ± 0.8	15.7 ± 36.1 %
Partial Alkalinity (mg $CaCO_3$ L^{-1})	13.1 ± 4.9	1.2 ± 14.7 %	13.3 ± 4.7	0.4 ± 10.7 %
Total Alkalinity (mg $CaCO_3$ L^{-1})	19.3 ± 6.9	2.4 ± 12.6 %	19.7 ± 6.8	0.5 ± 10.3 %
Conductivity (S m^{-1})	0.5 ± 0.1	0.0 ± 0.1 %	0.5 ± 0.1	0.0 ± 0.1 %
Dissolved Oxygen (mg L^{-1})	7.7 ± 0.4	1.9 ± 10.5 %	7.8 ± 0.4	0.1 ± 4.3 %
Zeta potential (mV)	-19.2 ± 1.4	5.7 ± 8.6 %	-18.5 ± 2.0	9.2 ± 9.4 %
Particle size (nm)	234.0 ± 43.7	17.3 ± 18.8 %	255.1 ± 92.2	9.0 ± 40.3 %

Table 4 Overall mean values for water quality parameters in disinfected water and mean removal/variation rates when compared to the filtered water from the household slow sand filters with a diffuser (HSSF-d) and the household slow sand filters with a float valve (HSSF-f), for the same period.

Parameter	HSSF-d disinfected		HSSF-f disinfected	
	Mean value ± SD	Mean removal/variation ± SD	Mean value ± SD	Mean removal/variation ± SD
Turbidity (NTU)	2.3 ± 3.4	0.4 ± 25.8%	2.6 ± 4.1	2.2 ± 29.7 %
Escherichia coli (CFU 100mL^{-1})	< 1 ± 1	0.7 ± 0.6 log	< 1 ± 0	0.6 ± 0.6 log
Total coliforms (CFU 100mL^{-1})	7 ± 13	0.9 ± 0.5 log	7 ± 10	0.9 ± 0.4 log
Giardia spp. cysts in 48 L	N/A	0.0 ± 0.0	N/A	0.0 ± 0.0
Cryptosporidium spp. oocysts in 48L	N/A	0.1 ± 0.1	N/A	0.1 ± 0.2
Apparent colour (HU)	9.7 ± 13.6	25.2 ± 34.0%	11.2 ± 16.3	19.7 ± 28.1%
True colour (HU)	7.5 ± 11.9	29.8 ± 39.7%	8.6 ± 14.5	-2.7 ± 98.7
pH	6.7 ± 0.7	4.2 ± 10.2%	6.8 ± 0.7	4.2 ± 9.8%
Temperature (ºC)	20.1 ± 2.1	0.0 ± 0.0%	20.1 ± 2.1	0.0 ± 0.0%
Absorbance (λ=254 nm)	0.04 ±0.05	-15.9 ± 134.1 %	0.04 ± 0.04	7.7 ± 16.4%
Dissolved Organic Carbon (mg L^{-1})	2.0 ± 0.5	-8.7 ± 34.6 %	1.7 ± 0.5	-0.8 ± 38.9%
Partial Alkalinity (mg CaCO3 L^{-1})	12.7 ± 4.5	8.6 ± 7.7%	12.5 ± 4.1	7.8 ± 8.8%
Total Alkalinity (mg CaCO3 L^{-1})	17.6 ± 7.8	14.6 ± 26.7%	17.6 ± 7.2	14.4 ± 26.0%
Conductivity (S m^{-1})	83.0 ± 36.2	-72.0 ± 57.9 %	83.8 ± 40.3	-77.4 ± 72.0 %
Dissolved Oxygen (mg L^{-1})	7.7 ± 0.4	-0.9 ± 2.7 %	7.7 ± 0.4	0.1 ± 2.4%
Zeta potential (mV)	-20.4 ± 2.8	-7.8 ± 17.5 %	-22.2 ± 4.0	-28.2 ± 31.3%

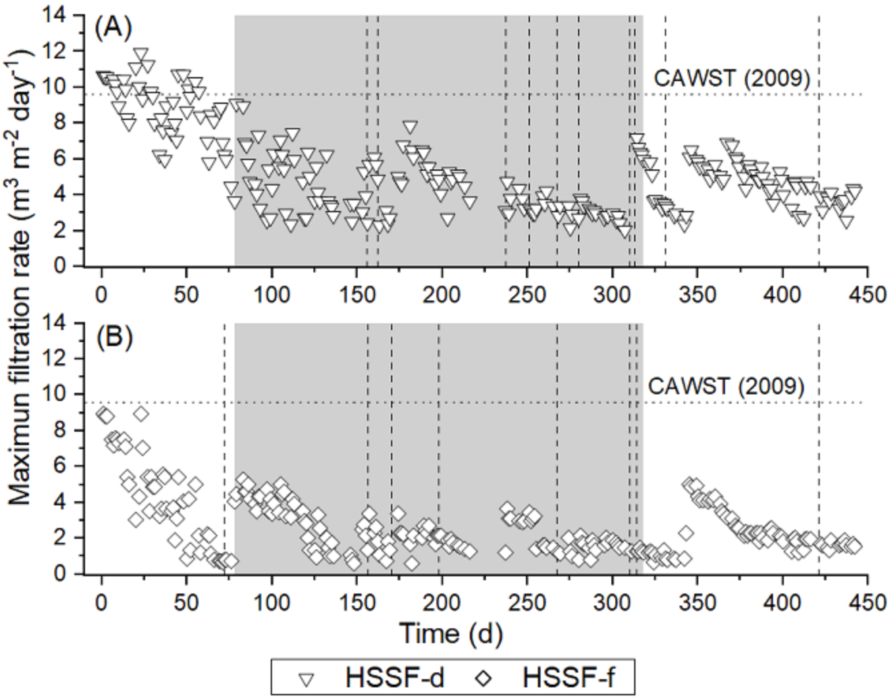
Particle size (nm)	241.1 ± 26.7	8.1 ± 9.1%	260.1 ± 58.1	-0.3 ± 24.6%
Free chlorine ($mg L^{-1}$)	1.4 ± 0.4	N/A	1.4 ± 0.4	N/A
Total chlorine ($mg L^{-1}$)	1.5 ± 0.4	N/A	1.5 ± 0.4	N/A

Figure 1



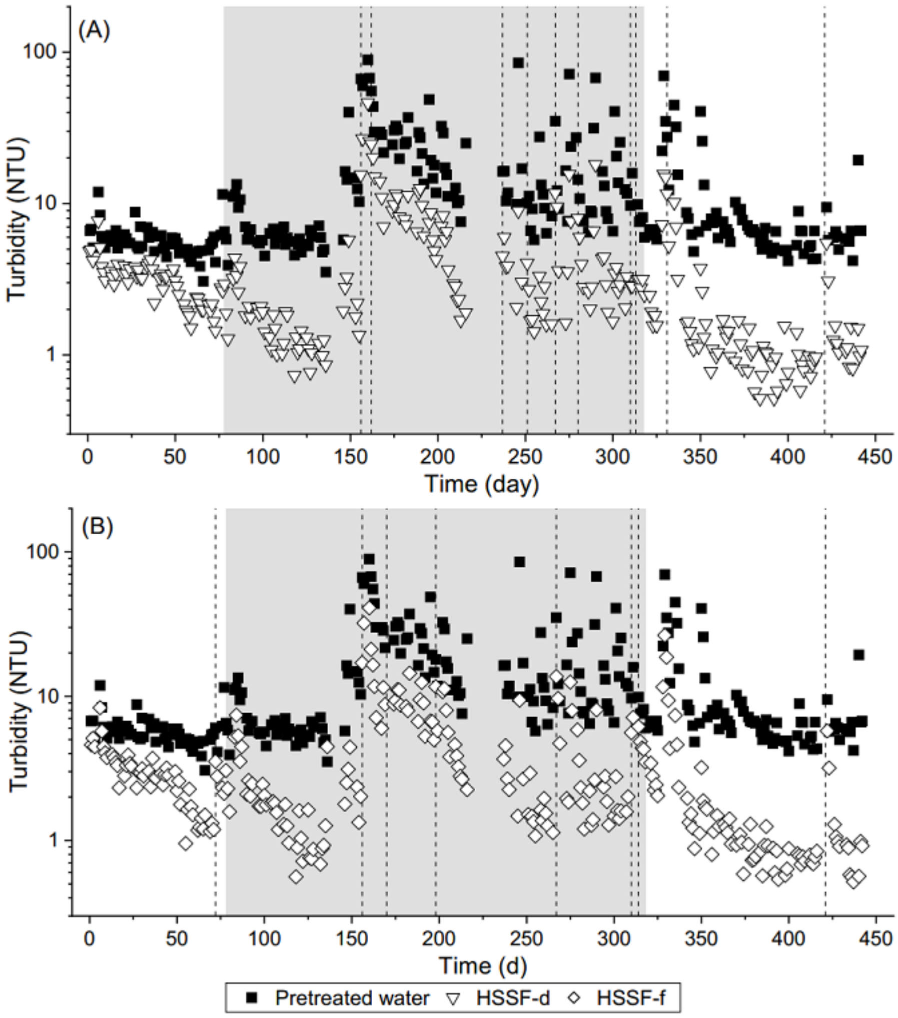
Gravity filter float valve
Synthetic fabric
Piezometers
Breathing hole
125.5 cm
108.0 cm
Diffuser vessel
Minimum water level (5cm)
Outlet tubing
Filtration media (50 cm)
Separation layer (5 cm)
Support layer (12.5 cm)

Figure 2



(A)
(B)
CAWST (2009)
CAWST (2009)
Maximun filtration rate (m3 m-2 day-1)
Time (d)
HSSF-d
HSSF-f

Figure 3



(A)
Turbidity (NTU)
100
10
1
0
50
100
150
200
250
300
350
400
450
Time (day)
(B)
Turbidity (NTU)
100
10
1
0
50
100
150
200
250
300
350
400
450
Time (d)
Pretreated water
HSSF-d
HSSF-f

Figure 4

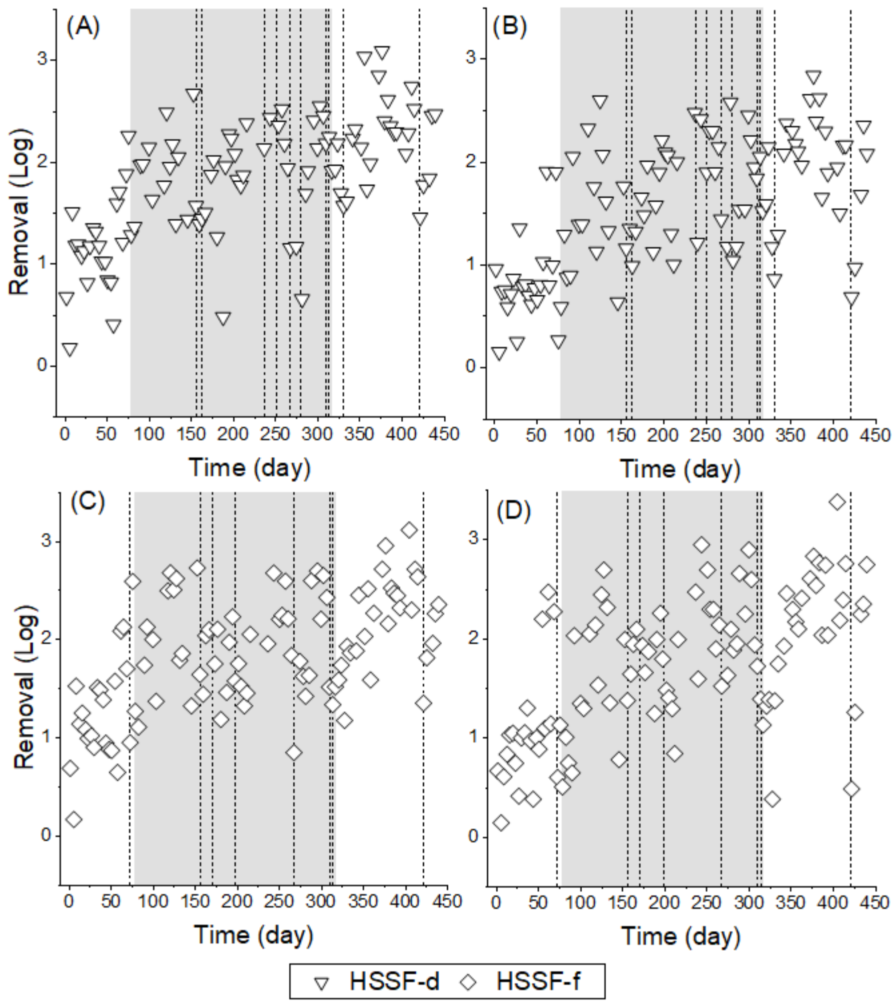
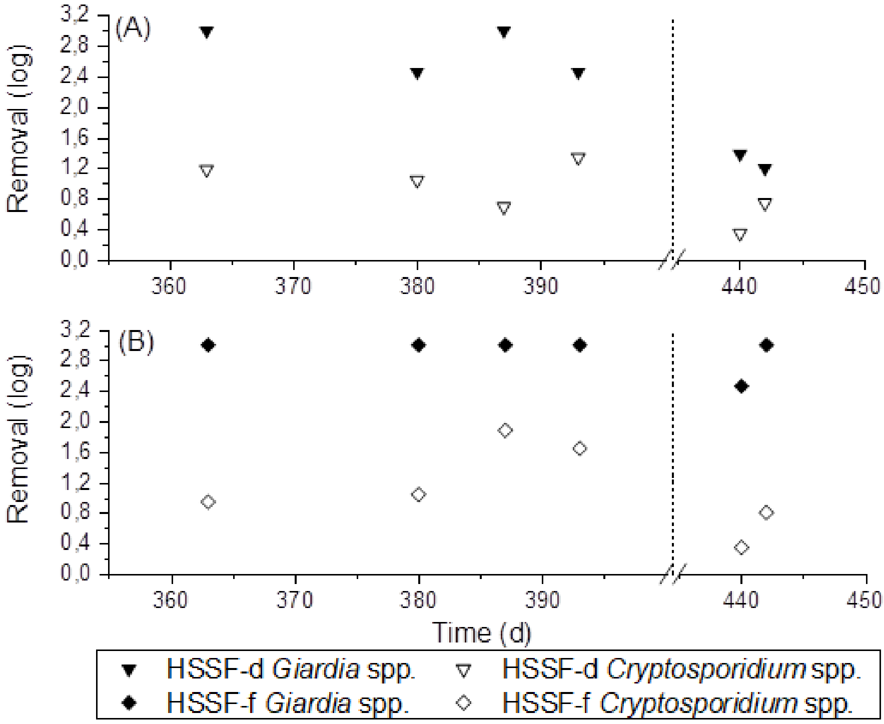


Figure 5



(A)
Removal (log)
3,2
2,8
2,4
2,0
1,6
1,2
0,8
0,4
0,0
360
370
380
390
440
450
(B)
Removal (log)
3,2
2,8
2,4
2,0
1,6
1,2
0,8
0,4
0,0
360
370
380
390
440
450
Time (d)
HSSF-d *Giardia* spp.
HSSF-d *Cryptosporidium* spp.
HSSF-f *Giardia* spp.
HSSF-f *Cryptosporidium* spp.

Figure captions

Figure 1. Household slow sand filter models studied. (A) Household slow sand filter with a float valve (HSSF-f). (B) Household slow sand filter with a diffuser (HSSF-d).

Figure 2. Maximum filtration rate (MFR) during operation time. (A) Household slow sand filter with diffuser (HSSF-d). (B) Household slow sand filter with float (HSSF-f). Note: Vertical dashed lines = complete maintenance (simplified maintenance not shown); Horizontal dashed lines = reference value 9.6 $m^3 m^{-2} day^{-1}$ (CAWST, 2009); White background = Dry season; Grey background = Rainy season.

Figure 3. (A) Pretreated water turbidity and remaining turbidity in filtered water from a household slow sand filter with a diffuser (HSSF-d). (B) Pretreated water turbidity and residual turbidity in filtered water from the household slow sand filter with a float valve (HSSF-f). Vertical dashed lines = complete maintenance (simplified maintenance not shown); White background = Dry season; Grey background = Rainy season.

Figure 4. (A) Total coliform removal by household slow sand filter with a diffuser (HSSF-d). (B) *E. coli* removal by household slow sand filter with a diffuser (HSSF-d). (C) Total coliform removal by household slow sand filter with a float valve (HSSF-f). (D) *E. coli* removal by household slow sand filter with a float valve (HSSF-f). Vertical dashed lines = complete maintenance (simplified maintenance not shown); White background = Dry season; Grey background = Rainy season.

Figure 5. (A) *Giardia* spp. and *Cryptosporidium* spp. removals by household slow sand filter with a diffuser (HSSF-d). (B) *Giardia* spp. and *Cryptosporidium* spp. removals by household slow sand filter with a float valve (HSSF-f). Vertical dashed lines = complete maintenance.