Household slow sand filters with and without water level control: continuous and intermittent flow efficiencies

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This work was supported by the São Paulo Research Foundation (FAPESP) under Grant Process 2014/12712-8; by the National Council for Scientific and Technological Development (CNPq) under Grant Process 442163/2014-2 and by CNPq for the PhD scholarship awarded to Paulo Marcos Faria Maciel.

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Four household slow sand filters were made out of PVC and operated in continuous and intermittent flows, with and without using a float to control the maximum level of water inside the units. The efficiency was evaluated as a function of *Escherichia coli* reduction and turbidity in water from the study prepared with kaolinite and *E. coli* suspension. The correlation of the efficiencies with the following operational parameters was evaluated: operating time, time after maintenance, filtration rate and head loss divided by bed thickness. The filters were classified as intermittent with float (IFF), intermittent without float (IF), continuous with float (CFF) and continuous without float (CF). IFF, CFF and CF had a non-woven blanket installed on top of the media. The results indicated that no significant statistical differences were found in *E. coli* reduction and turbidity between IFF and IF, however the former had filter runs over 80 days and the latter almost a quarter of this value. CFF matured faster and had less turbidity remaining in relation to CF. When comparing IFF with CFF, the former presented lower turbidity remaining (0.89 ± 0.44 NTU versus 1.24 ± 0.91NTU), but a lower reduction of *E. coli* (1.40 ± 0.61 log versus 2.29 ± 0.74 log). The time after maintenance was the most important operational parameter when evaluating the efficiencies. The float helped to mature the filter more quickly in a continuous flow and, together with a non-woven blanket, extended the filter runs in the intermittent flow.

Keywords: biosand filter, drinking water, *Escherichia coli*, point-of-use treatment, turbidity.

Introduction

Problems related to the lack of adequate sanitation are still a concern worldwide. In 2015, 844 million people were deprived of basic drinking water services [1]. As a consequence of this and the lack of other sanitation facilities, there were more than 800 thousand deaths due to diarrhoeal diseases [2]. In the same year, in Latin America and the Caribbean, 5% of the population did not have access to drinking water (31.5

million) [3] and, specifically in Brazil according to the Diagnosis of Water and Sewage Services [4], 16.7% of the population lacked a water distribution network.

In populations not served by distribution networks, interventions aimed at combating the microbiological risk of point-of-use drinking water are important provisional measures [5] in conjunction with public health surveillance activities to provide support to target consumers [6]. Among the point-of-use water treatment technologies, Household Slow Sand Filters (HSSFs) have important characteristics, such as low investment, simple maintenance and daily production of safe water, as long as the biological layer of the filter is mature.

HSSF with intermittent flow and continuous flow

HSSF is an adaptation of the conventional slow sand filter (SSF), however designed to operate in batch mode (intermittent flow). This adaptation to the intermittent regime was possible by maintaining a shallow water layer above the sand bed (standing water layer) [7] and feeding the unit bound to a retention period and the porosity of the filter bed. Similar to SSF, proper sizing and operation provide the necessary conditions for forming the biological layer (*schmutzdecke*) [8].

The intermittent HSSF receives the dose of water to be treated 1 to 4 times a day, with a recommended maximum filtration rate of 9.6 m^3 m^{-2} d^{-1} [9]. The filtration rate in this filter is declining. The interval between the time the water stops flowing from the filter outlet and a new inflow of influent water is called the pause period, recommended being a minimum of 1 hour [9]. Alternatively, the operating parameter total water retention time in the filter is used, which is the time between one water feed and the next one [10], is used.

HSSF in continuous flow is dependent on the constant input and controlled water flow rate. In SSF, the filtration rate can vary from 1.7 to 7.2 m^3 m^{-2} d^{-1}, depending on the influent water quality [11]. There are no still no evaluations concerning filtration rates of HSSF in continuous flow. This operating regime is more efficient in reducing microorganisms when compared to intermittent HSSFs, treating the same daily volume of water (3.71 log versus 1.67 log for *Escherichia coli* reduction) [12]. However, this configuration needs to be studied in more depth, for example, to be adapted to a full scale without depending on water supply pumping, thus not needing electrical energy.

HSSF technology evolution

Since they were created in the early 1990s, intermittent HSSFs have been implemented in countries such as Ethiopia [13], the Dominican Republic [14], Kenya [15] and Ghana [16]. The technology is considered successful because it has average levels of adoption of 94% in the first 24 months after installing them, however the lack of ongoing support and physical breakage are pointed out as the main reasons for households stopping using HSSF [17].

Operational parameters have been adjusted over the years considering the results obtained from various studies [12, 18–21]. For example, the volume of water to be dosed in the filter is suggested to be less than or equal to its void volume of the filter bed [22, 23] and a high reduction of microorganisms can be reached with a longer pause period and lower maximum water level above the top of the filter media [10].

HSSF construction

HSSF can be made out of plastic or concrete. There are disadvantages to using the latter material such as needing to be knowledgeable about civil construction, waiting a long time for the cement to dry and difficulties of moving the ready unit due to its weight and size. An HSSF made out of plastic such as the *Hydraid*® [24] is not heavy and can be installed quickly, however the unit is provided by specialised companies and is costly.

The aims of this study were: i) to evaluate the construction of the HSSF using PVC pipes and fittings typical of building hydraulic installations; ii) to assess the maturation of the HSSF when the water to be treated presents a low concentration of nutrients; iii) to evaluate the head loss development over time, the turbidity and the *E. coli* reduction efficiencies between intermittent and continuous filters, with and without using floats for water level control; iv) to weigh up the correlation between performance parameters (remaining turbidity and *E. coli* reduction) and operating parameters.

Four HSSF models adapted to the reality of isolated communities in Brazil were constructed. The use of a non-woven blanket at the top of the filter media was also predicted in the study. The Mann-Whitney hypothesis test was used to compare the means of each parameter between a pair of filters. The Kruskal-Wallis test was used to compare the means of each parameter among all the filters. The duration of filter runs was also weighed. The operational parameters, operating time, time after maintenance, filtration rate and head loss divided by the bed thickness with the HSSF efficiencies were correlated.

Material and Methods

HSSF construction

The basic HSSF model that was researched is shown in Figure 1. The unit was built using PVC pipes and fittings typical of building hydraulic installations. The base was a 250 mm diameter siphoned box coupled to a 1.0 m high tube of the same diameter. The outlet piping was positioned 4.0 cm above the top of the filter media to maintain the standing water depth.

[Figure 1 near here]

The basic HSSF model received a support layer formed by 7.5 cm of coarse gravel (stones from 12 to 15 mm), 5 cm of fine gravel (stones from 5 to 8 mm) and 5 cm of coarse sand (grains from 1.5 to 3 mm). The fine sand filter media was 58 cm thick with grains between 0.075 mm and 1 mm, effective diameter (D_{10}) 0.13 mm and uniformity coefficient (UC) of 1.46. The abovementioned materials were purchased in hardware stores and were also collected from a river in the city of Analândia, São Paulo state, Brazil. Before introducing the filter media, water was added to the filter body in order to prevent pockets of air from forming and allowing stratification of the sand.

The intermittent filter with float (IFF) received a 14 L (bucket) reservoir with a coupled float controlling the water level (Figure 2a). The intermittent filter without float (IF) had a 14 L reservoir with a perforated bottom with 1.3 mm holes (Figure 2b), which was the most similar to the Center of Affordable Water and Sanitation Technology (CAWST) model [9]. The continuous filter with float (CFF) had a float installed on the side of the filter connected to a raised 150 L reservoir (Figure 2c). The continuous filter without a float (CF) received a perforated reservoir identical to that of the IF and received water from a 150 L high reservoir, controlled by ball registration and maintained at 22 mL min^{-1} (Figure 2d). The IFF, CF and CFF models received an easy-to-access non-woven blanket purchased from a haberdashery shop (thickness 2.8 mm with 25 µm fibres), installed on the top of the filter media.

[Figure 2 near here]

The function of the float in the intermittent filter was to limit the maximum water level (maximum filtration rate) above the standing water layer. It should be noted that, although the float minimized the maximum water level, it did not reduce the volume that can be added to the unit. The float enables us to add a volume equal to the reservoir above it. Without the float, the volume poured into the filter will be limited by the free space between the standing water and the maximum water level inside the filter body, consequently generating a high maximum filtration rate.

Tracer tests

Hydrodynamic tests were run to evaluate the flow. Sodium chloride was used as a tracer with a concentration of 100 mg L^{-1}. The tests were carried out with step-like stimuli as the presence of the standing water layer above the filter media promoted diffusion from the tracer, which would make the pulse-like stimulus tests susceptible to errors. The curves were obtained by reading the conductivity at the HSSF output using a probe with a Go!Link interface coupled to a computer with Logger Lite software (Vernier Software & Technology, USA).

In the CFF and CF, the tracer tests obtained the mean residence time of the water, important in determining the sample collection times. For the tests, the filtration rate of 0.68 m^3 m^{-2} d^{-1} (flow 22 mL min^{-1}) was fixed as it obtained a daily production of 32 L, needed to compare with the intermittent filters.

Normalisation of the data obtained from the NaCl (C(t)) concentration to obtain the F curve (Equation 1) was performed. Differentiation of the F curve led to the residence time distribution curve (curve E, according to Equation 2), from which it was possible to obtain the mean residence time - t_m (Equation 3).

$$F(t) = \frac{C(t)}{C_{max}} \qquad (1)$$

$$\frac{dF}{dt} = E \qquad (2)$$

$$tm = \int_0^\infty t.E(t).dt \qquad (3)$$

Where:

F - Normalised tracer concentration curve

C - Tracer concentration (mg L^{-1})

E - Residence time distribution function

t_m - Mean tracer residence time in the filter (min)

Influent water

The water from the study was a mixture of water from a well with kaolinite (18 mg L^{-}) to obtain a mean turbidity of 10 NTU. Afterwards, *Escherichia coli* suspension (ATCC 11229) was added with a mean value of 10^3 Colony Forming Unit (CFU) 100 mL^{-1}. The aim of the water from the study was to evaluate the maturation of the filters having few nutrients, a challenge faced when treating groundwater.

Analyses and sampling

The water supply in the intermittent filters occurred daily at 9:00 am and 5:00 p.m., and therefore there were two total water retention times in the filter (interval between one dose to the next), 8 h and 16 h. The volume of each dose of water in the intermittent filters was 16 L. Each filter (intermittent or continuous) produced 32 L daily and a 0.5 L sample was collected to evaluate the turbidity, *E. coli* and other parameters of interest (absorbance at λ= 254 nm, total organic carbon - TOC, electrical conductivity, apparent colour and pH). Standard Methods [25] were followed to evaluate the aforementioned parameters.

Performance analyses (remaining turbidity and *E. coli* reduction efficiency) were considered for the longer total water retention time in the intermittent filters (16 h). For the continuous filters, water collected after the calculated mean residence time (Equations 1 to 3) was considered.

The HSSFs had seven piezometers and readings were taken to evaluate the evolution of the head loss throughout the operation. To facilitate the study, the head loss

(Δh) divided by the length of the filter media (L) at the following points, L = 52 cm and L = 2 cm, was considered.

Filter cleaning

The filters were cleaned when the daily production of the units was not as desired (32 L). Maintenance consisted of removing the blanket and scraping the solids left in it. Then, the blanket was washed in water until it was clean.

For the IF, without a blanket, cleaning followed the CAWST procedures [9] which consisted of stirring the entire surface area of the filter media with the fingers (alternately with a glass rod in this research), being careful not to disturb more than 1.0 cm of sand depth. After stirring, the sand was allowed to settle for one minute and all the supernatant water was discarded in a plastic container; 5 L of water was added and the procedure was repeated until the top of the filter media was clean.

Statistical analyses

The Mann-Whitney non-parametric test, with a significance level of 5% and null hypothesis of equal means, was used to compare the *E. coli* reduction efficiency and turbidity between comparative pairs of intermittent filters (IFF versus IF) and continuous (CF versus CFF). To compare the means of more than two groups, the Kruskal-Wallis test was used, also with 5% significance, with the post hoc Mann-Whitney pairwised test.

Bivariate analyses were performed to investigate the correlation between performance parameters of interest (*E. coli* reduction and remaining turbidity) and the following operating parameters: operating time; time after maintenance; maximum filtration rate (in intermittent filters); and head loss divided by the length of the filter bed ($\Delta h \ L^{-1}$) in every filter media and also at the top. In addition to these parameters, the correlation with the remaining turbidity and the concentration of *E. coli* influent was included for the *E. coli* reduction; and for the remaining turbidity, the influent turbidity. The correlation was considered significant when the probability of no correlation (p-value) was less than 5%, together with the correlation coefficient *r* greater than the *r-crítical*, according to the table of critical values of the Pearson correlation coefficient found in Larson and Farber [26]. Statistical tests were performed using the PAST software - PAlaeontological STatistics, manufactured by Hammer et al. [27].

Results

Filter construction

It took one person 18 hours to build an HSSF (8 hours to wash the granular materials, 6 hours for sieving and 4 hours for sawing the tubes in the filter body). The cost of each unit in Brazil (São Paulo state) was US$ 97 in February, 2017 including labour and materials. The built units were lightweight, making them easy to transport.

Influent water

The characteristics of the water from the study are shown in Table 1 and a low TOC value can be observed. Turbidity in the influent water varied a little as a result of kaolinite sedimentation. A high standard deviation of the *E. coli* concentration in the water from the study was observed. The fact was due to the random growth of the colonies by incubation in nutrient broth the day before the tests, detecting that concentration inoculated 24 h after mixing the influent water of the filter. Other characteristics of the water from the study and HSSF effluent are shown in Table S1, in the supplementary materials of this article.

[Table 1 near here]

Tracer tests

In the tracer tests, the mean water residence time in the continuous HSSFs was calculated according to Equation 3, obtaining values of 16 h and 31 min for the CFF and 14 h and 36 min for the CF. The difference of these values took place because CFF presented a greater thickness of standing water compared to CF as a result of installing the float (Figure 2).

Filtration rate

The change in the maximum filtration rate throughout the intermittent filter operation is shown in Figure 3.

[Figure 3 near here]

The float installed in IFF made sure there was less amplitude of the maximum filtration rate since the maximum level of the water was kept constant at 10 cm above the standing water layer. In the IF, the maximum water level was 34 cm, with consequent higher maximum filtration rate at the beginning of the filter runs, compared to the IFF.

Head loss development and HSSF operating time

Figure 4 shows the head loss of the 4 HSSFs studied, expressed as the reading difference between the first and last piezometer (Δh) divided by the thickness of the top filter media to the last piezometer (L=52 cm).

[Figure 4 near here]

In the intermittent filters, IFF (Figure 4a) and IF (Figure 4b), there was little change in the readings of the last piezometers. Differently, continuous HSSFs showed progression of head loss with responses in the last piezometer along the filter runs (Figure 4c for CFF and 4d for CF).

Retention of impurities in HSSFs occurred predominantly at the top of the filter media. Figure 5 shows the head loss expressed by the reading difference between the first and second piezometers (Δh) divided by the thickness of the top filter media up to this piezometer (L=2 cm) for the studied HSSF models.

[Figure 5 near here]

In IFF, the head loss at the top of the filter media (Figure 5a), at the beginning of the filter run, was higher than that of IF (Figure 5b). This was because there was no blanket on the top of the IF filter media. However, at the end of the filter runs, the IF head loss was higher than that of the other filters, due to the compaction of the top of the filter media, which was prevented in the units in which the non-woven blanket was installed. In the supplementary material of this research, the head loss in each sublayer of the filters studied can be found in Figures S1 to S4.

Turbidity removal

Remaining turbidity of the HSSFs is shown in Figure 6 for the intermittent filters with 16 h retention time (Figure 6a) and for the continuous filters (Figure 6b). Prior to day 23, IF and IFF showed similar turbidity removal efficiency, both removing on average 85% turbidity over the period considered. However, in the operating time between days 23 and 83, there was a significant difference between the remaining IFF turbidity (mean of 0.81 ± 0.47 NTU) and IF (mean of 1.26 ± 0.86 NTU). After this period, there was no statistical difference between the remaining turbidity of IF and IFF.

[Figure 6 near here]

Regarding the continuous filters, the average efficiency in CFF turbidity removal was statistically higher than that of CF. CF presented a longer delay in the stabilisation of the parameter in the two filter runs studied. A summary of the turbidity removal results is shown in Table 2. The intermittent filters had, statistically, better efficiency compared to the continuous ones for this parameter.

[Table 2 near here]

***E. coli* reduction**

The *E. coli* reduction as a function of time with corresponding temperature is shown in Figure 7a, for intermittent HSSFs with 16h total retention time, and 7b, for the continuous filters. IFF and IF were close to 0.5 log of *E. coli* reduction on the 14th day of operation. After the 30th day, the efficiency in reducing *E. coli* from IFF was greater than 1.0 log. On the other hand, the IF was unable to reduce more than 1.0 log of the bacterium in all tests during the period considered, due to frequent maintenance. Although IF efficiency was decreased when reducing *E. coli* after maintenance, there was no statistical difference between the IFF and IF throughout the operation for this parameter.

[Figure 7 near here]

The continuous filters showed efficiency in reducing *E. coli* almost always higher than 1.0 log, the only exception being the reduction of 0.90 log per CFF on the 14th day. There was no statistical difference in the reduction of this bacterium between CFF and CF.

The efficiency means of *E. coli* reduction in the intermittent and continuous filters are shown in Table 3. In contrast to the results of turbidity removal, the continuous flow filters were more efficient in reducing the microbiological risk compared to the intermittent ones.

[Table 3 near here]

During the operation there were 2 records of atypical temperatures coincident with the *E. coli* analysis (Figure 7). The temperature of 12ºC on day 113 was reflected in a decrease in efficiency in reducing *E. coli* from the continuous HSSFs in relation to the previous measurement. These efficiency declines were from 2.27 to 1.47 log of *E. coli* and from 1.82 to 1.02 log of *E. coli*, respectively for CFF and CF.

When the temperature was at 15°C, on day 153, the IFF and IF performances in reducing *E coli* also fell, respectively, from 2.55 to 1.31 log and from 1.89 to 1.16 log, relative to the previous test (day 147).

Bivariate analyses

The results of Pearson's correlation coefficient and the p-value (probability of no correlation) of the *E. coli* reduction and remaining turbidity with operational parameters are shown in Table 4 for the intermittent HSSFs with a total retention period of 16 h, and for continuous HSSFs.

[Table 4 near here]

The parameter time after maintenance, correlated significantly with the *E. coli* reduction in IFF, CFF and CF. There was no significant correlation between the *E. coli* reduction and the IF operational parameters. In IFF, there was also a correlation between the *E. coli* reduction with the maximum filtration rate and the head loss in the first 2 cm. In CFF, the operating time was the parameter with the highest correlation coefficient with *E. coli* reduction.

Remaining turbidity correlated significantly with time after maintenance for all the groups analysed. The operating time had the highest correlation with the parameter (turbidity) for IFF, the head loss divided by the filter bed up to 52 cm for CFF and the time after maintenance for IF and CF. The remaining turbidity did not correlate with the influent turbidity in any of the filters. This result indicates that the studied filters did not suffer from the effect of fluctuation of the influent turbidity in the water clarification, when the parameter was controlled and near 10 NTU.

Discussion

Filter construction evaluation

The cost of each HSSF in PVC was higher up to US$ 60 when compared to the concrete version [28]. However, the concrete HSSF usually demands efforts of a group of workers in the multiple steps of its construction [9]. For instance, four people are usually required to transport the filter to any distance [29]. The concrete filter depends on having specific tools to make the metallic mould that sets the cement, which may prevent the technology from spreading in isolated communities in Latin American countries.

It should be noted that the costs spent on tools to make the concrete filter can reach US$ 1,000 [29]. The HSSF studied here has intuitive assembly and parts can be easily found in hardware stores. Another advantage of the PVC model is that it does not require specific tools (e.g. a mould of the HSSF concrete version). The cost presented in the Results section is related to building a single model and this value tends to be reduced if the quantity of units produced is increased or if the parts and materials are donated by institutions or companies.

Influent water implications

Groundwater has been reported as a source of supply in 50% of sites with HSSFs installed [17], however the technology performance when treating water with few nutrients has not been studied much in the scientific literature. The low TOC value in the water influent to the HSSFs was desired in this study aiming to evaluate the maturation of the filters in this extreme condition.

Various published studies have used influent water with a higher concentration of TOC, between 5 and 12 mg L^{-1}, from a natural source [30] or by adding a fraction of sewage to the influent water [31–35].

The increase in nutrients in influent water to HSSFs has been used to simulate the presence of sewage in springs typical of developing countries and to accelerate the process of filter maturation [23]. In waters with these characteristics, the maximum value of *E. coli* reduction is reached in periods between 40 and 50 days [12, 23, 36]. In this research, the maximum reduction value of the bacteria occurred near the 70th day for the intermittent filters (2.3 log) and double the time for the continuous filters, which reached 3.4 log reduction. However, the continuous filters showed more efficiency than the intermittent ones for this parameter during the entire operation. In this context, methods to accelerate the HSSF ripening are recommended. It should be noted that HSSFs needed time after maintenance to recover from their performance [31], as they present a normal period of instability.

Filtration rate

The decay of filtration rate throughout the operation is related to the improvement of HSSF in the reduction of microorganisms [18, 23, 34, 36–38]. However, if the rate drop is significant, the HSSF operation must be interrupted to clean it and this can happen after short periods, as in the IF (Figure 3b).

The maximum filtration rates of IF and IFF varied between 9.0 and 0.8 m^3 m^{-2} d^{-1} and between 4.6 to 0.9 m^3 m^{-2} d^{-1} (Figure 3), respectively, always below the CAWST maximum recommendation [9]. Other studies evaluated the maximum filtration rates between 21.6 and 2.4 m^3 m^{-2} d^{-1} [10, 12, 18]. The best efficiencies for *E. coli* reduction in IFF occurred when the maximum filtration rate was found close to 1 m^3 m^{-2} d^{-1} and in IF with values of 3 m^3 m^{-2} d^{-1}. Similarly, in a study carried out by Elliott et al. [23], the reduction efficiency of the bacteria increased from 1.2 log, when the maximum filtration rate was 7.2 $m^3 m^{-2} d^{-1}$, for 3.5 log, at the end of the filter run (maximum filtration rate of 2.4 $m^3 m^{-2} d^{-1}$).

The filter runs in experiments with HSSFs have duration records from 50 days [23] to 86 days [33]. IF presented 9 to 32 days filter runs, values lower than those in the literature and IFF, which had two runs, lasting 84 and 85 days. Factors such as sand specifications, filter media thickness, filtered daily volume and influent water quality may explain variations in the filter runs of different studies.

In this study, the maximum level control with float in conjunction with the IFF blanket installation resulted in filter media runs almost four times higher than IF. Restarting the filter run is associated with the decrease in efficiency of the unit [39], therefore it is desirable for the filter to have prolonged filter runs.

Head loss development

The head loss on all IF media was almost 3 times higher than IFF, CF and CFF (Figure 4). This was due to higher filtration rates resulting from the available hydraulic head of 34 cm above the standing water level soon after being added to the unit. As a consequence of the high head loss, the IF filter runs were short. The other filters had compatible values among them of head loss divided by media thickness and there was no difference in the duration of filter runs between them.

In Figure 4, few changes of the head loss are noted in the last piezometer of the intermittent filters along the filter runs. In IF, the total head loss remained close to 31 cm and in IFF by 10 cm. In intermittent HSSF from Campos and Outhwaite [40] the total head loss ranged from 6 to 10.4 cm in a 40 cm filter media, D_{10} 0.18 mm and UC 1.65.

On the other hand, in the CF and CFF continuous filters there was an increase in the head loss with responses in the last piezometer. In these units, the filtration rate remained constant and the retention of impurities at the top of the filter media decreased the hydraulic load available on that piezometer.

The total head loss in CF and CFF ranged from 2.6 cm to 10.5 cm. Young-Rojanschi and Madramootoo [12] did not observe significant changes in the continuous filter piezometer readings, possibly due to adopting lower filtration rates (0.24 m^3 m^{-2} d^{-1}) and for a shorter time (58 days) compared to the present study, in addition to a different media specification (D_{10} 0.17 mm and UC 2.06).

The dynamics of the head loss at the top of the filter media (Figure 5) more clearly reflects the evolution of the filter runs in all the HSSFs studied. The head loss proportional to the top filter media thickness was often higher than that of the whole bed. In fact, by definition, schmutzdecke is a layer in which the head loss is disproportionate to its thickness [11].

In addition, the top of the filter media has finer grains, in which there is greater head loss compared to the rest of the filter, even with the clean bed. The installation of the HSSF is done by adding water before the sand causes stratification of the filter media, as observed by Young-Rojanschi and Madramootoo [30] on an acrylic column.

Turbidity removal

The remaining IFF turbidity was lower than that achieved by the IF in some periods of the operation because there were more maintenance events in the IF (Figure 6). It should be observed that the IFF operated with a lower filtration rate when compared to the IF (Figure 3). However, in the more advanced operating period the IF appeared to have acquired greater resilience against the effect of maintenance on turbidity.

Singer et al. [39] also observed a slight difference in turbidity removal (95.6% versus 94.7%) in the recovery period after maintaining the intermittent HSSF with 18 h retention time.

Previous studies, which operated intermittent HSSFs with influent turbidity close to the studied range, showed initial efficiency of removal of this parameter between 79% and 83%, and finally 92% [21, 36]. IFF and IF presented 83% of turbidity removal in the first 7 days with an average considering the whole operation of 91% and 89% of removal, respectively.

The results in Figure 6 showed that intermittent HSSFs can consistently produce water with turbidity below the value recommended by the World Health Organization – WHO of 1.0 NTU [6] for chlorination to be effective. The turbidity values in these filters were always below the maximum accepted by the WHO of 5.0 NTU [6]. Considering all IFF and IF operation periods, respectively 69% and 60% of the effluent samples showed turbidity of less than 1.0 NTU.

The best turbidity result remaining from CFF compared to CF was possibly due to the delay in developing the biological layer in the latter. In CF, there was a drop of 26 cm in the water in its inlet (Figure 2d). Moreover, an additional 6 cm of standing water in CFF compared to CF (Figure 2) possibly helped the kaolinite sedimentation above the non-woven blanket. CFF and CF had, respectively, 40% and 22% of samples with turbidity below 1 NTU. Only at two moments did the turbidity exceed the maximum recommended by the WHO of 5.0 NTU, after cleaning, in the two filters, and on the first day of the CF operation.

The best turbidity removal efficiency of the intermittent filters compared to the continuous ones, according to Table 2, was the opposite result to that obtained by Young-Rojanschi and Madramootoo [12]. These authors investigated a lower filtration rate than this one for continuous filters. In addition, the filtration mechanisms involved in turbidity retention in intermittent filters may have acted better for water in the present study (well water with kaolinite addition) compared to continuous filters.

Higher filtration rates in intermittent filters when compared with continuous ones may have caused sand pore obstruction on the top layer and this phenomenon favoured the kaolinite retention, and consequently, turbidity removal.

***E. coli* reduction**

The 1.0 log *E. coli* reduction is the threshold established for HSSF technology by the WHO [6] .This value was reached by IFF in the period of operation close to 30 days (Figure 7), similarly to other studies [18, 23, 31]. On the other hand, IF underwent maintenance in this important period and was unable to maintain reductions above 1.0 log. The mean values of *E. coli* reduction in IFF and IF in all operations (Table 3) were in the expected range according to the literature for intermittent filters [10, 18, 32], between 1.15 log and 1.7 log.

Both continuous filters showed the maximum 3.5 log *E. coli* reduction. This value is less than the maximum reduction of approximately 5.0 log of Young-Rojanschi and Madramootoo´s continuous filters [12]. However, there were methodological differences between the present study and this research, which carried out the collection in a period of 24 h withdrawing a composite sample to analyse the presence of the bacterium. In the present study, these analyses were performed immediately after the collection, considering the residence time of the water in the filter obtained in the tracer tests.

The finding of the best efficiencies of the continuous filters in reducing *E. coli* compared to the intermittent ones (Table 3) confirmed, on a full scale, the results of Young-Rojanschi and Madramootoo [12] on a bench scale. In addition, unlike intermittent HSSFs, continuous HSSFs showed a rapid recovery of efficiency in reducing *E. coli* after cleaning the top of the filter media.

Decreases in temperature affected the efficiency of HSSFs in *E. coli* reduction. This fact confirms the observation of an experiment under controlled temperature conditions [41], in which the reduction in temperature from 18ºC to 12ºC caused the reduction in the bacteria from 90% (1 log) to 79% (0.68 log).

By comparing the the 4 HSSF models studied, the CFF presented the best performance according to microbiological efficiency criterion followed by turbidity removal. This filter had better efficiency in reducing *E. coli* among all the filters, with no statistical difference compared to CF, however with lower turbidity remaining in comparison to the latter.

From the operational point of view the CFF was simpler than the CF. In the latter, the inlet flow suffered variations due to a reduction in the level of the reservoir and obstruction of the ball registration by solid particles, variations that are obstacles to the user´s control. In addition, the HSSF Intermittent Level Control (IFF) model can be adapted for continuous operation, with flow control filtered by logging at the outlet, which would eliminate the need for a high reservoir and enable the diffusion of units with a continuous flow.

Bivariate analyses

The results of the bivariate analyses (Table 4) demonstrated that the time after maintenance is an important operational parameter for HSSF. This parameter correlated significantly with the *E. coli* reduction (with the exception of IF) and the remaining turbidity. In convergence with these results, Kennedy et al. [31] found the recovery time after cleaning for 17 days to achieve 1.0 log reduction of thermotolerant coliforms in intermittent HSSFs. Nair et al. [33] also observed a decrease in efficiency to reduce microorganisms after maintenance.

In a different way, Napotnik et al. [42] found no significant correlation between *E. coli* reduction and the operational parameters in a 9-month study, including time after maintenance. Factors such as frequency of analysis can help to understand differences of results between different studies. These authors found a significant correlation between remaining turbidity and the filtration rate, which was also shown in the present study.

E. coli reduction was correlated with turbidity only in IFF. In the present study, high turbidity removal was achieved rapidly by intermittent filters. Nevertheless, those filters experienced a delay in reaching high values of *E. coli* reductions (i.e. values higher than 1.2 log), as the maintenance had an impact on their efficiency. On the other hand, maintenance also altered the turbidity removal in the continuous filters. However, the *E. coli* reduction (i.e. 2.2 log reduction 15 days before maintenance and 2.3 log reduction 4 days after maintenance in CFF) remained practically unchanged. Napotnik et al. [42] also found no correlation between these two parameters. These results suggest that low turbidity cannot be used as a microbiological risk indicator; therefore, posterior disinfection is always recommended, even with low turbidity of the filtered water.

Conclusions

HSSFs made of PVC have advantages in terms of being easy and fast to assemble, regardless of knowing about civil construction, producing lightweight and easily transportable units. The units were more expensive compared to other studies, however they required simpler and cheaper tools.

The HSSF operation using water poor in nutrients resulted in a delay in the filter maturation. The best efficiency for *E. coli* reduction occurred in about 70 days for intermittent filters and in 140 days for continuous filters.

When comparing the continuous filters studied, the CFF was able to produce water with remaining turbidity statistically lower than that of CF, however there was no statistical difference for the *E. coli* reduction.

When comparing the intermittent filters, there was no statistical difference for the *E. coli* reduction and turbidity. The IFF presented filter runs with an average duration of 84 days, while the IF had media runs of 24 days, which shows that the IFF was able to produce water with better quality for a longer time.

The continuous filters proved to be more efficient for the *E. coli* reduction compared to the intermittent ones. The continuous filters also showed a faster recovery of bacterial reduction efficiency after maintenance. On the other hand, the intermittent filters had lower remaining turbidity.

The time after maintenance was the operational parameter with the highest correlation with the *E. coli* reduction, considering all the filter models tested. For the remaining turbidity, the operating time was the parameter most strongly correlated for IFF, the head loss in every filter bed for CFF and the time after maintenance in IF and CF, which was also important in the first two.

Acknowledgements

The authors would like to thank the São Paulo Research Foundation (FAPESP - Brazil), Process nº 2014/12712-8 and the National Council for Scientific and Technological Development (CNPq), Process 442163/2014-2 for the funding; and CNPq for the doctoral scholarship granted to Paulo Marcos Faria Maciel.

Disclosure Statement

No potential conflict of interest was reported by the authors

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Table 1. Characteristics of water from the study

Parameter	Water from the study of the continuous HSSFs	Water from the study of the intermittent HSSFs
	Mean ± standard deviation	
Turbidity (NTU)	11.75 ± 5.87	10.92 ± 5.02
E. coli (CFU 100 mL^{-1})	3.969 ± 4184	5.021 ± 6765
Total Organic Carbon - TOC (mg L^{-1})	0.28 ± 0.14	0.59 ± 0.28

HSSF – Household Slow Sand Filter

Table 2. Turbidity removal in continuous and intermittent Household Slow Sand Filters (HSSF)

HSSF	Turbidity Influent (NTU)	Turbidity remaining (NTU) (filtered water)	Statistical comparison* of means
	Mean ± standard deviation		
IFF	10.92 ± 5.02	0.89 ± 0.44	< CF; < CFF; = IF
IF	10.92 ± 5.02	1.04 ± 0.66	< CF; < CFF; = IFF
CFF	11.75 ± 5.87	1.24 ± 0.91	< CF; >IF; > IFF
CF	11.75 ± 5.87	1.90 ± 1.36	> IFF; >IF; >CFF

***Statistical comparison by the Kruskal-Wallis test with 5% significance and Mann-Whitney a posteriori test; Inequality signals (“<” lower or “>” higher) or equality (“=”) indicate, respectively, whether or not the HSSF model has a mean of the statistically different parameter of the comparative model; IFF and IF: intermittent HSSF with float and without float, respectively, with 16 h of retention time in the filter; CFF: continuous HSSF with float; CF: Continuous HSSF without float.**

Table 3. Efficiency of *E.coli* reduction in continuous and intermittent Household Slow Sand Filters (HSSF)

HSSF	*E. coli* influent to the HSSFs (CFU 100 mL^{-1})	*E. coli reduction* (log) (filtered water)	Statistical comparison * of means
	Mean ± standard deviation		
IFF	5.021 ± 6.765	1.40 ± 0.61	< CFF <CF; = IF
IF	5.021 ± 6.765	1.26 ± 0.45	< CFF; <CF; = IFF
CFF	3.969 ± 4.184	2.29 ± 0.74	>IFF; >IF; = CF
CF	3.969 ± 4.184	2.14 ± 0.73	> IFF; >IF; = CFF

***Statistical comparison by the Kruskal-Wallis test with 5% significance and Mann-Whitney a posteriori test; Inequality signals (“<” lower or “>” higher) or equality (“=”) indicate, respectively, whether or not the HSSF model has a mean of the statistically different parameter of the comparative model; IFF - intermittent HSSF with float IF– HSSF intermittent without float; CFF – HSSF continuous with float; CF – HSSF continuous without float.**

Table 4. Bivariate analysis of the E. coli reduction and remaining turbidity with Pearson´s correlation coefficients between Household Slow Sand Filters (HSSF) operating parameters

		E coli reduction						
		Time(days)	Time A.M. (days)	MFR	Δh L^{-1} L= 0 to 52 cm	Δh L^{-1} L= 0 to 2 cm	Turbidity (filtered water)	*E. coli* Influent
IFF (n=18)	|r|	0.239	**0.838**	**0.727**	0.429	**0.789**	**0.470**	0.434
	p	0.340	**<0.001**	**0.007**	0.075	**<0.001**	**0.049**	0.072
IF (n=18)	|r|	0.383	0.443	0.340	0.321	0.291	0.334	**0.500**
	p	0.117	0.065	0.167	0.194	0.257	0.175	**0.035**
CFF (n=19)	|r|	**0.640**	**0.482**		**0.536**	**0.522**	0.432	0.234
	p	**0.003**	**0.037**		**0.018**	**0.022**	0.065	0.335
CF (n=19)	|r|	0.448	**0.473**		0.112	0.024	0.337	0.339
	p	0.054	**0.041**		0.648	0.924	0.158	0.155
		Turbidity (filtered water)						
		Time (days)	Time A.M. (days)	MFR	Δh L^{-1} L= 0 to 52 cm	Δh L^{-1} L= 0 to 2 cm	Turbidity Influent	
IFF (n=51)	|r|	**0.585**	**0.457**	**0.512**	**0.336**	**0.397**	0.094	
	p	**<0.001**	**<0.001**	**<0.001**	**0.017**	**0.004**	0.516	
IF (n=51)	|r|	**0.489**	**0.532**	**0.353**	0.210	**0.383**	0.097	
	p	**<0.001**	**<0.001**	**0.015**	0.157	**0.008**	0.515	
CFF (n=38)	|r|	**0.554**	**0.614**		**0.644**	**0.632**	0.032	
	p	**<0.001**	**<0.001**		**<0.001**	**<0.001**	0.851	
CF (n=39)	|r|	0.327	**0.592**		**0.377**	**0.401**	0.078	
	p	0.042	**<0.001**		**0.018**	**0.011**	0.639	

Time: days from the beginning of the operation; A.M. time: days after maintenance of the top of the filter media; Δh L^{-1}, head loss in the piezometer divided by the thickness of the filter bed to the piezometer (L); MFR: maximum filtration rate; |r|: Pearson's correlation coefficient modulus; p-value: probability of non-correlation; IFF: intermittent HSSF with float; IF: intermittent without float; CFF: continuous HSSF with float; CF: continuous HSSF without float; n: number of associations. In bold, significant correlation (p <0.05 and r> critical r), p <0.001 indicates strong correlation, for n = 18, critical r = 0.468; n = 19, critical r = 0.456; n = 51, critical r = 0.279; n = 38 and n = 39, critical r = 0.334.

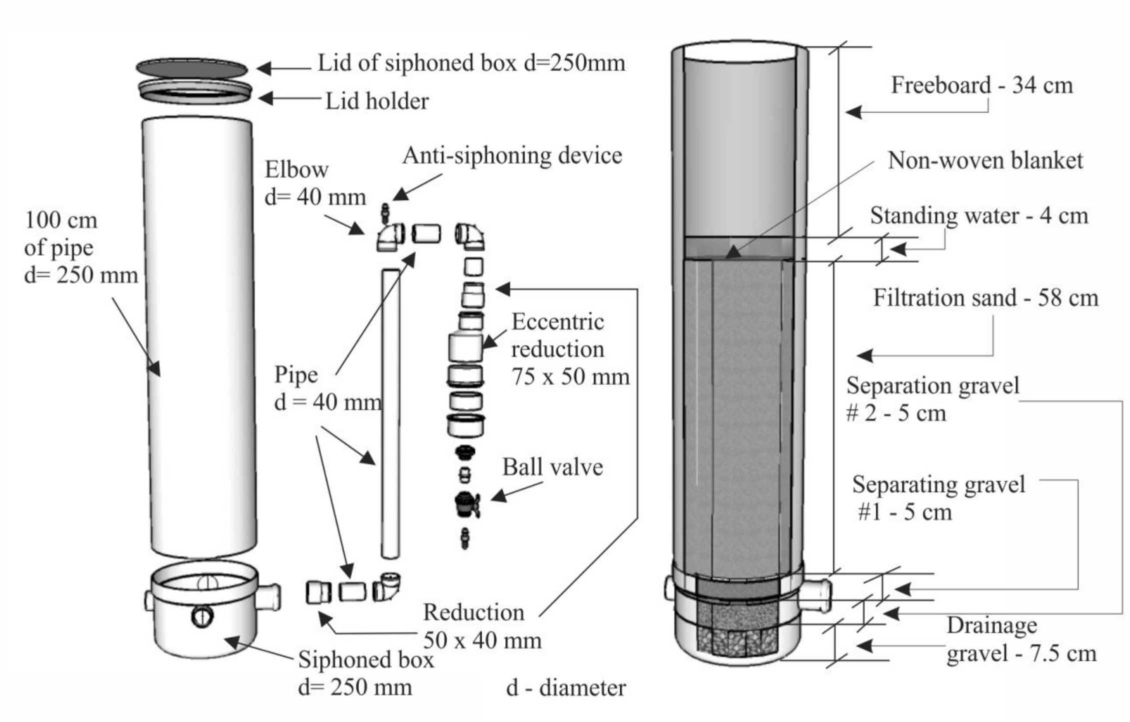

Figure 1. Basic Household Slow Sand Filter model studied.

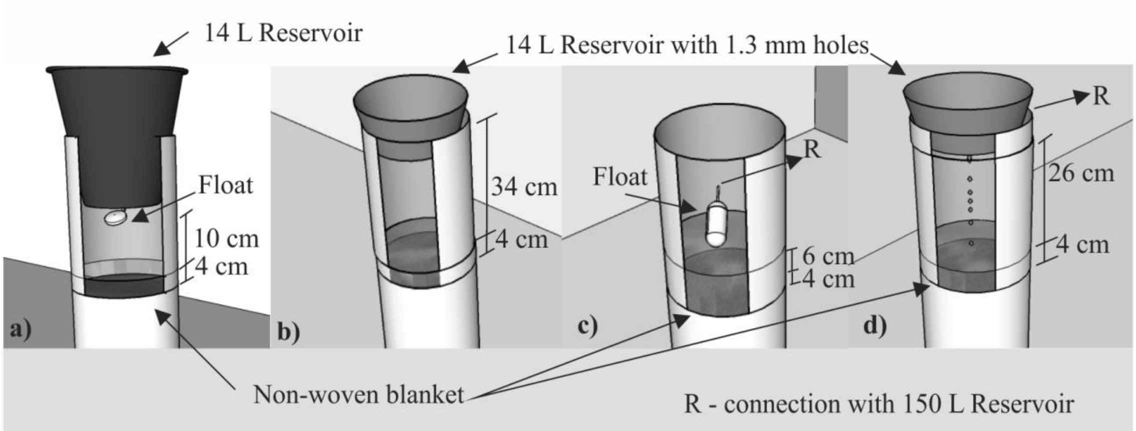

Figure 2. Household Slow Sand Filters: (a) intermittent with float - IFF; (b) intermittent without float - IF; (c) continuous with float - CFF; and (d) continuous without float - CF.

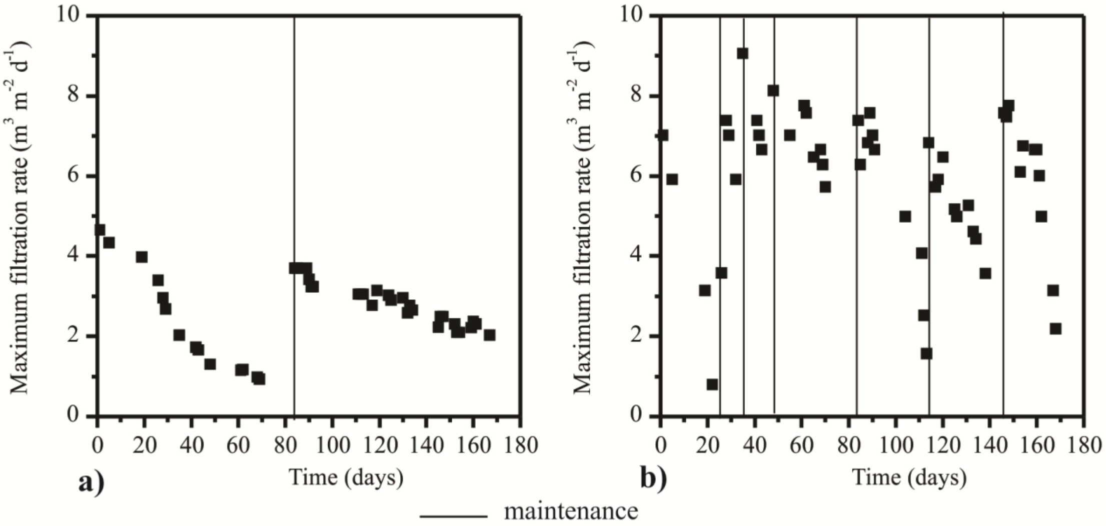

Figure 3. Change of the maximum filtration rate in intermittent Household Slow Sand Filters (a) with float - IFF and (b) without float – IF.

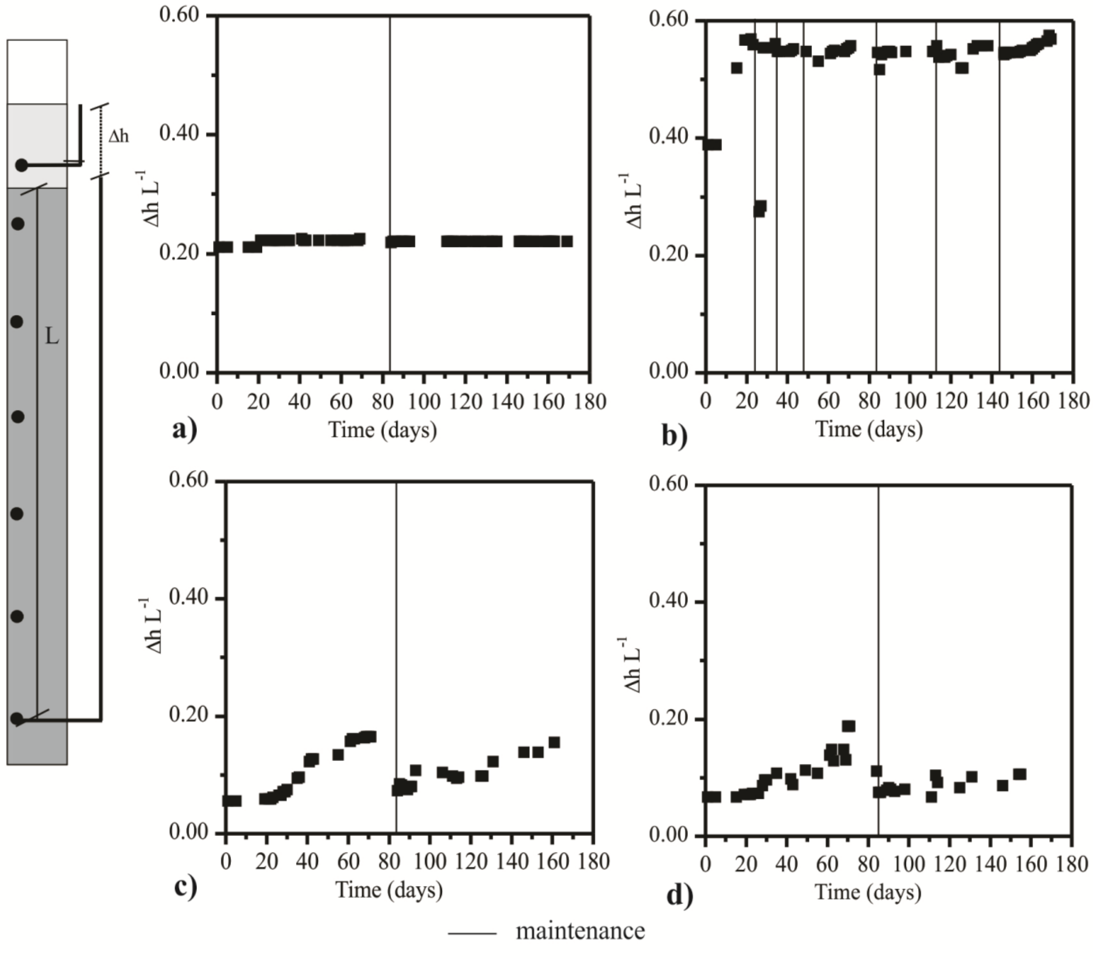

Figure 4. Head loss between first and last piezometer (Δh) divided by the thickness from the top filter media to the last piezometer (L=52 cm) in an Household Slow Sand Filters: (a) intermittent with float (IFF); (b) intermittent without float (IF); continuous with float (CFF); and continuous without float (CF).

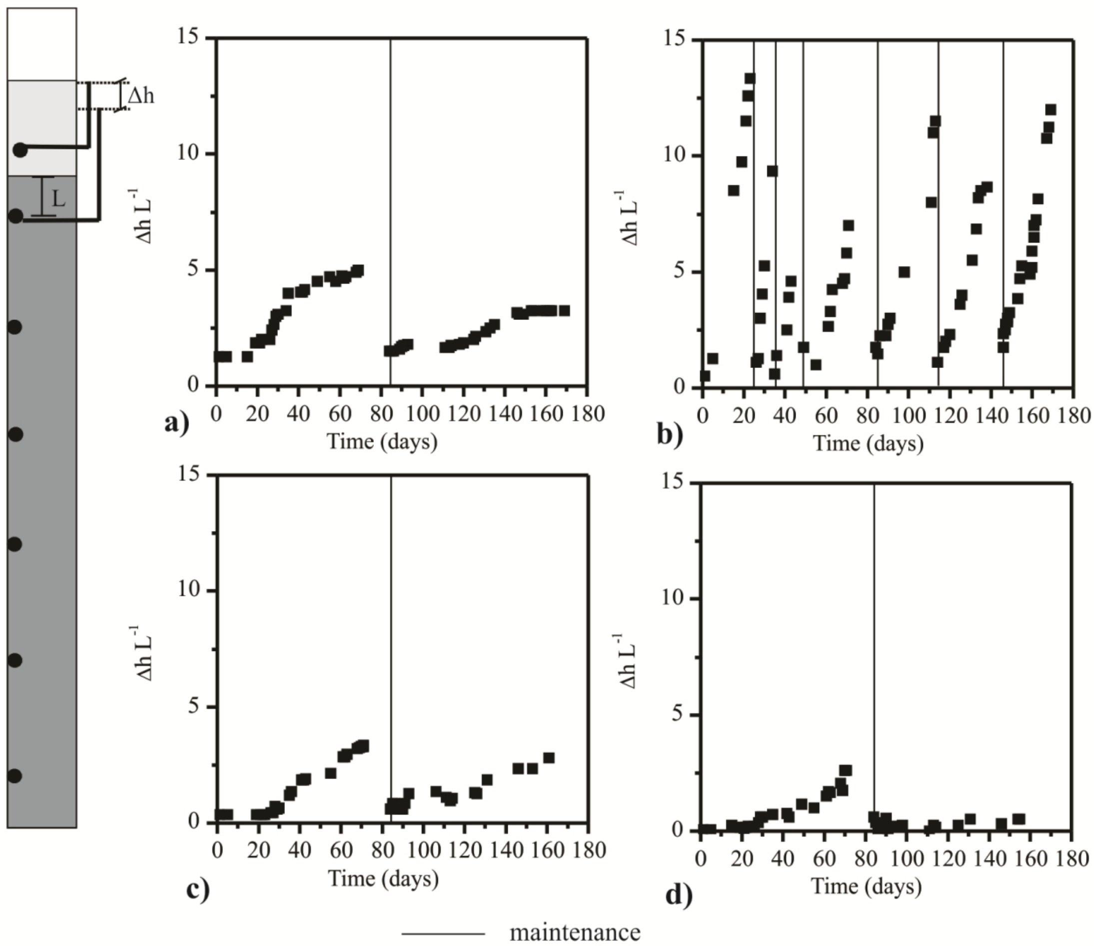

Figure 5. Head loss between the first two piezometers (Δh) divided by the thickness of the filter media from the top to the second piezometer (L=2 cm) in an Household Slow Sand Filters: (a) intermittent with float (IFF); (b) intermittent without float (IF); (c) continuous with float (CFF); and (d) continuous without float (CF).

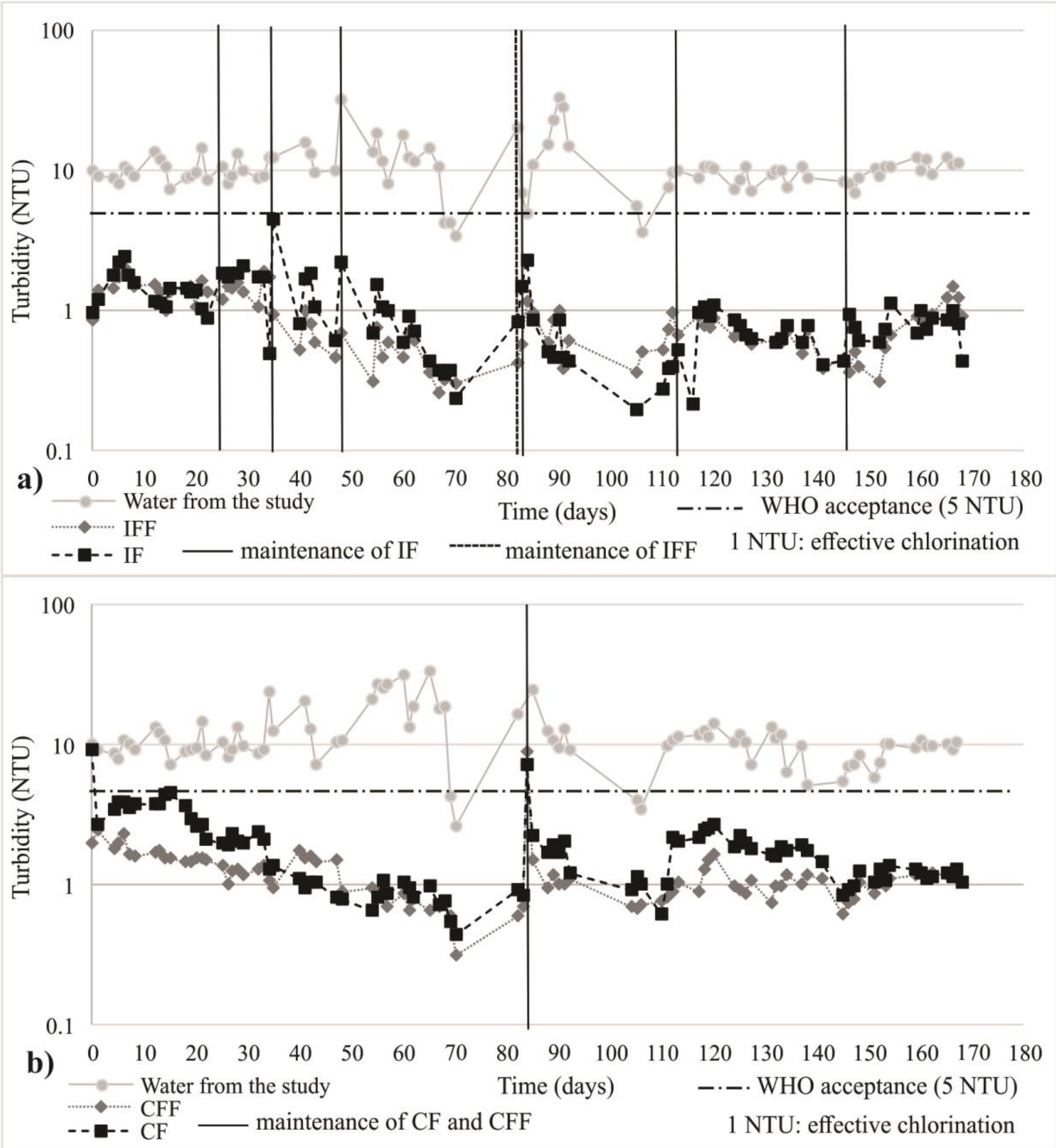

Figure 6. Remaining turbidity in the filtered water of Household Slow Sand Filters: (a) intermittent with float (IFF) and without float (IF) and (b) continuous with float (CFF) and without float (CF).

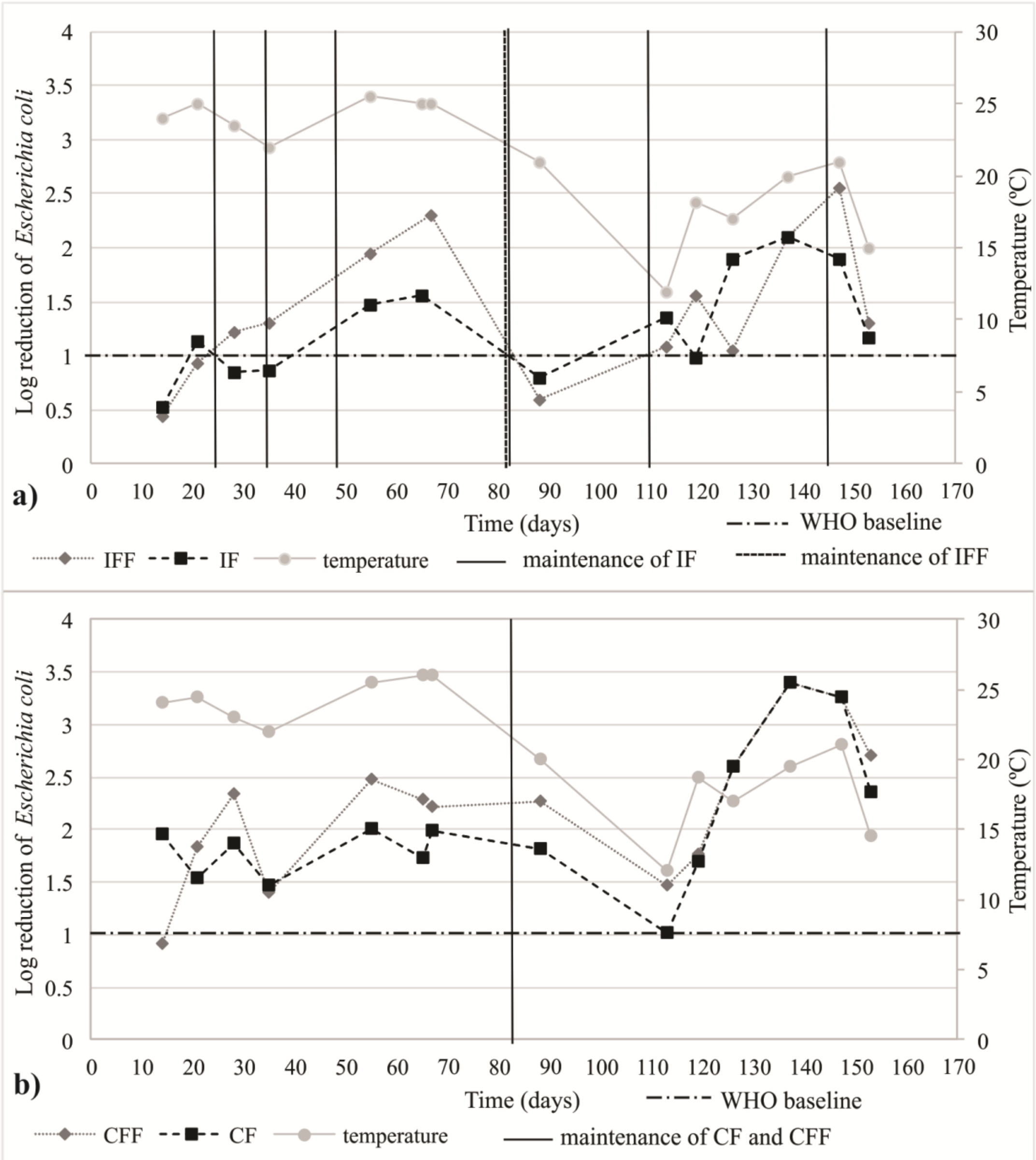

Figure 7. *Escherichia coli* reduction as a function of time and with corresponding temperature in Household Slow Sand Filters: (a) intermittent with float (IFF) and without float (IF) and (b) continuous with float (CFF) and without float (CF).